TRANSIENTS ON TRANSMISSION LINES

BY

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ARMOUR INSTITUTE OF TECHNOLOGY

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Transients on transmission
lines and modern protective

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TRANSIENTS ON TRANSMISSION LINES AND MODERN PROTECTIVE DEVICES

A THESIS

PRESENTED BY

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TO THE

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IN

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MAY 27, 1920

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CHAPTER I.

INTRODUCTION.

In the last three decades a very rapid progress was made in the generation and the distribution of electrical energy. The ever increasing demand for electrical power brought about a phenomenal growth in the size of generating equipment, especially in the centers of industry and of population. At the Columbian exposition was exhibited then the largest alternator in the world. It had a capacity of 750 k.v.a. To-day many single units carry a continuous load of 50,000 k.v.a. For economical transmission high voltage had to be employed. The phenomena occuring in these high voltage, high power circuits, under a steady flow of power, and normal conditions are well understood, and can be predetermined and calculated with little difficulty. The limitations of the apparatus, however, are found in the abnormal conditions which often occur. The transient abnormal

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voltages, frequencies, and currents often rise to destructive magnitudes, endangering the apparatus and the continuity of service. It is then the purpose of this thesis to make an investigation of the origin, character, and magnitude of these transients, and to describe and discuss the modern protective devices.

With every electrical circuit three phenomena are inseparably associated:

1) Energy is consumed by being converted into heat,

2) Electrostatic field and

3) Electromagnetic field,

appear in the space surrounding the conductor. According to Maxwell the electrostatic field is ether distortion and the electromagnetic field is ether motion. Hence each field represents a certain amount of stored energy.

Let w = energy in the electrostatic field.

C = the capacity of the circuit.

In order to produce the electrostatic field, power p,

had to be supplied by the circuit.

Now, power = current x voltage.

or $p = ei$

If e is the voltage of the electrostatic field, let i'= current which was consumed in the circuit to establish the field.

By definition $C = \frac{i'}{\frac{de}{dt}}$

then $i' = C\frac{de}{dt}$ (1)

the energy supplied to establish the field is

$$w' = \int_0^e eidt \qquad (2)$$

Substituting from equation (1) we get

$$w' = \int_0^e Ce\frac{de}{dt}dt = C\int_0^e e\,de = \qquad (3)$$

$\frac{1}{2}Ce^2$..........the enery of the (4)

dielectric field.

A similar equation can be developed for the enery in the magnetic field

Let w'= energy in the magnetic field

L = inductance of the circuit.

e'= voltage consumed in the

establishment of the magnetic field; by definition

$$e' = L\frac{di}{dt} \tag{5}$$

Energy supplied to establish the field $= \int_0^i e' i \, dt$

Substituting for e' from equation (5)

$$W = L\int_0^i e' i \, dt = L\int_0^i i\frac{di}{dt}\,dt = L\int_0^i i \, dt = \tfrac{1}{2}Li^2$$

the energy stored in the magnetic field. From the equations $w = \frac{1}{2}Li^2$ and $w' = \frac{1}{2}Ce^2$ we see that the amount of energy stored in the electric field depends upon the current and the voltage of the line.

A change in the circuit conditions then generally requires a change in the amount of the stored energy. Since this change can not occur instantly we then have, at every change in the circuit conditions, a transient period, during which the circuit adjusts itself to the change of stored enery. The transient therefore, is an intermediate between two permanent conditions.

A transient is not exclusively an electrical phenomena. It occurs wherever energy storage, in any form, occurs. Thus, if we start a

motor car, we have a transient period of acceleration before a constant speed is reached. During that time the car is gathering the mechanical energy of its momentum. The car can not be stopped instantly, and a transient condition of retardation intervenes, during which the energy of its momentum must be dissipated, before the car comes to rest. The water-hammer is a familiar example of an enery transient. A rapid stoppage of flow in a long high head water pipe might lead to a pressure transient, high enough to burst the pipe. Hence the use of relief valves, surge tanks, etc., to take up and dissipate the energy stored in the momentum of the moving column of water.

SINGLE ENERGY TRANSIENTS.

As has been shown in the previous section, the energy storage in an electric circuit can take place in two forms:

a) in the electrostatic field
b) " " magnetic "

However, in many circuits only moderate voltages (say up to 2000 volts) are used. Due to the low voltage and the limited extent of such a circuit (small capacity) the energy stored in the dielectric field is not appreciable compared to the energy in the magnetic field. We can then consider the energy storage to be in one form only. In such a case the change of stored energy can be either an increase or a decrease and no surging between the two forms can occur. Such a transient is then the simplest we can have. In what follows we will discuss a few single energy transients that may occur in an electric circuit.

a) The establishment of Current in an Inductive Circuit of Negligible Capacity.

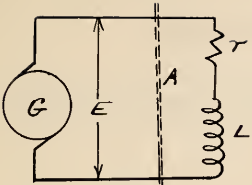

Fig 1.

In the circuit represented in fig (1) assume the generator G to be maintaining a constant electromotive force E. This electromotive force is partly consumed by the resistence r and partly by the self-inductance L.

According to Kirchhoff's law we have[*]

$$E = ri + L\frac{di}{dt} \qquad (7)$$

This is a differential equation where the variables are separable[†]. We can then write it after a little transformation as

$$\frac{-r\,di}{E-ri} = -\frac{r}{L}dt$$

Integrating, we get

$$\log\left(E-ri\right) = -\frac{rt}{L} + C$$

We can evaluate the constant C by the initial condition when $t = o \qquad i = o$

$$C = \log E$$

Subsituting m the above equation

[†] Cohen: Differential Equations P. 13

[*] Pender: Princ. of El. Eng. P. 288.

$$\log(E - ri) = -\frac{rt}{L} + \log E$$

Performing anti-logarithmation, we get

$$E - ri = \epsilon^{-\frac{rt}{L}} \cdot E \qquad \text{or,}$$

$$-ri = \epsilon^{-\frac{rt}{L}} \cdot E - E \qquad \text{or,}$$

$$i = \frac{E}{r}\left(1 - \epsilon^{-\frac{rt}{L}}\right) \qquad (8)$$

This equation shows that after a time sufficient to make $\epsilon^{-\frac{rt}{L}}$ sensibly zero, i approaches the limiting value E/r

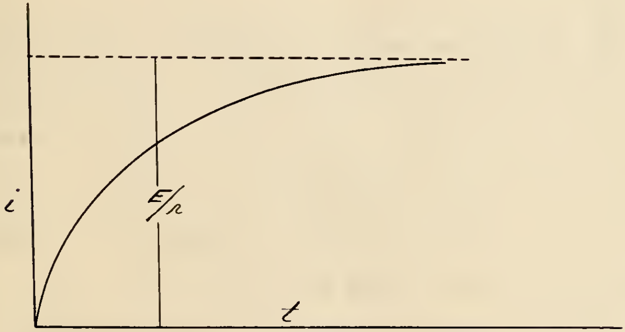

Fig 2.
Showing the growth of current in an inductive circuit.

Let us now write an equation for power in such a circuit. Obviously Ei = power supplied by the generator

i^2r = power dissipated as heat in the resistance r.

Multiplying each side of equation (7) by i we get

$$Ei = i^2r + iL\frac{di}{dt} \qquad (9).$$

taking the total energy between t = o and t = t_o we have

$$\int_0^{t_o} Ei\,dt = \int_0^{t_o} ri^2\,dt + \int_0^{t_o} Li\frac{di}{dt}\,dt$$

$\int_{t=0}^{t=t_o} Li\,di$ is then the energy stored in the magnetic field. Evaluating the integral that is equal to $\frac{1}{2}Li_o^2$ where i_o = current at the time $t = t_o$. This equation again shows us that the energy in the magnetic field $= \frac{1}{2}Li^2$.

Let us now see what happens when, after the establishment of a steady current in such a circuit, the voltage is withdrawn and without

changing the constants of the circuit the coil short-circuited as shown by A in Fig 1. With no voltage impressed the current must come down to zero. This, however, does not occur instantly since the flux must vanish and the energy of the magnetic field must be returned to the circuit.

Writing the equation for the inductive coil when the voltage is withdrawn and the circuit closed upon itself, we get

$$ir + L\frac{di}{dt} = 0 \qquad (11)$$

or $$ir = -L\frac{di}{dt}$$

Dividing both sides by i and transposing

$$\frac{di}{i} = -\frac{r}{L}dt \qquad (12)$$

Integrating, we get

$$\log i = -\frac{rt}{L} + C \qquad (13)$$

when $t=o$, $\frac{rt}{L} = 0$ and hence

$$\log i = \log i_0$$

where i_0 = the initial current. Rewriting (13)

$$\log i = -\frac{rt}{L} + \log i_0$$

or

$$i = i_0 \epsilon^{-\frac{rt}{L}} \qquad (14)$$

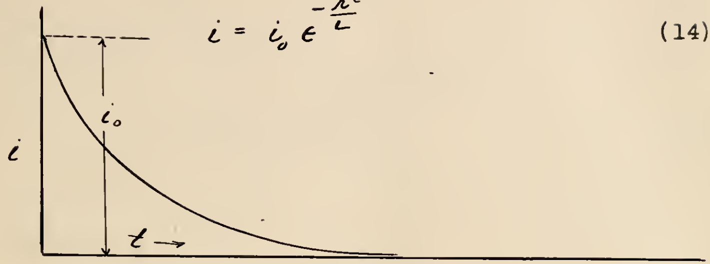

Fig 3.

We can thus see that the current decreases according to the logarithmic law. See Fig. 3.

The i^2r loss accompanying the decaying current i comes from the magnetic field. This can be shown as follows:

Let i = current at time t

by equation (14)

$$i = i_0 \epsilon^{-\frac{rt}{L}} \qquad (14')$$

Total energy dissipated as heat in the circuit equals

$$\int_0^\infty i^2 r\,dt \qquad (15)$$

Substituting for i from equation (14) we get

$$\text{Energy dissipated} = \int_0^\infty \left(i_0 \epsilon^{-\frac{rt}{L}}\right)^2 r\,dt = \qquad (16).$$

$$r i_0^2 \int_0^\infty \epsilon^{-\frac{2rt}{L}} \, dt \qquad (17)$$

Integrating we get

$$r i_0^2 \frac{L}{2r} \left[\epsilon^{-\frac{2rt}{L}} \right]_{t=0}^{t=\infty} \qquad (18)$$

Evaluating we get

$$\text{Energy dissipated} = \tfrac{1}{2} L i_0^2 \qquad (19)$$

in other words all of the energy of the magnetic field is dissipated as ri^2 loss.

While the current is dying out the potential difference of self induction accross the coil is equal to $-L\frac{di}{dt}$

Let e = counter voltage across the coil to self induction

$$e = -L\frac{di}{dt} \qquad (20)$$

Substituting in (20) the value of i from equation (14) we get

$$e = -L\frac{d\left(i_0 \epsilon^{-\frac{rt}{L}}\right)}{dt} = -L\left(-\frac{r}{L}\right) i_0 \epsilon^{-\frac{rt}{L}} \qquad (21).$$

$$e = r i_0 \epsilon^{-\frac{rt}{L}} \tag{22}$$

This voltage e is maximum when t = o then e = ri . In other words the counter-e.m.f. of self-induction is proportional to the change in current and to the resistence. When opening the circuit r $=\infty$, hence according to equation (22) e would be infinite. This however, is far from being the truth. We must bear in mind that we have neglected the effect of capacity in our equation. No physical circuit can possibly exist without having some definite capacity. Hence even if the voltage could rise to infinity the circuit would then have $\frac{1}{2} CE^2$ energy stored in it. C being finite and E infinite, we then would have an infinite amount of energy stored in it. So, if the circuit was interrupted instantaneously, and the insulation was such that it could withstand a very high voltage, the magnetic energy stored in the circuit would then reappear as dielectric energy. In other words, $\frac{1}{2} CE^2$ would become equal to $\frac{1}{2} L i^2$ and the highest possible voltage can

then readily be obtained.

$$\tfrac{1}{2} C E^2 = \tfrac{1}{2} L i^2 \qquad (23)$$

Multiplying by 2 and taking the square root, we get

$$E = i\sqrt{\frac{L}{C}} \qquad (24)$$

In other words $i\sqrt{\frac{L}{C}}$ is the limiting value of the voltage when the current i is interrupted instantaneously. Usually, however, the insulation breaks down long before that voltage is reached and the energy is then dissipated in the electrostatic discharge. In the case of a highly inductive circuit, as for instance the field winding of a shunt machine, the current can not be interrupted instantaneously; an arc always forms when the switch is opened.

The Transient State of a Circuit when an Alternating E. M. F. is Impressed.

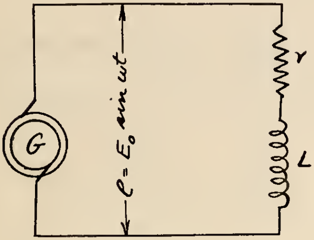

Fig. 4.

Let r = the resistance and L = the inductance of the circuit in fig 4.

Let e = $E_0 \sin \omega t$, be the impressed e.m.f.

If i = the current when the voltage is e, we have by Kirchoff's law,

$$ri + L\frac{di}{dt} + e = 0 \qquad (25)$$

Substituting $E_0 \sin \omega t$ for e and transposing we get,

$$\frac{r}{L}i + \frac{di}{dt} = \frac{E_0}{L}\sin \omega t \qquad (26)$$

This equation can be solved by the use of the integrating factor* since $\frac{E_0}{L}\sin \omega t$ is a function of t only and $\frac{r}{L}$ is a constant.

Hence our integrating factor is

$$\epsilon^{\frac{r}{L}\int dt} = \epsilon^{\frac{rt}{L}}$$

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[*] Campbell: Diff. Eq. P.22

Hence coming back to equation (26) we can write

$$i\epsilon^{\frac{r}{L}t} = \frac{E_0}{L}\int \epsilon^{\frac{r}{L}t} \sin \omega t \, dt + C \qquad (27)$$

In Peirce's Short Table of Integrals (Form 239) we can get a form for integrating eq. 27.

$$\int \epsilon^{\frac{rt}{L}} \sin \omega t \, dt = \frac{\frac{r}{L}\sin \omega t - \omega \cos \omega t}{\frac{r^2}{L^2} + \omega^2}\epsilon^{\frac{rt}{L}} + C$$

Now we can write equation (27) as

$$i\epsilon^{\frac{r}{L}t} = \frac{E_0}{L}\left(\frac{\frac{r}{L}\sin \omega t - \omega \cos \omega t}{\frac{r^2}{L^2} + \omega^2}\right)\epsilon^{\frac{rt}{L}} + C \qquad (28)$$

Multiplying the numerator and the denominator by L^2 we get,

$$i\epsilon^{\frac{rt}{L}} = E_0\left(\frac{R\sin \omega t - \omega L \cos \omega t}{R^2 + L^2\omega^2}\right)\epsilon^{\frac{r}{L}t} + C \qquad (29)$$

Now, write z for $\sqrt{R^2+\omega^2L^2}$ (the impedance) (30)

and let $\phi = \tan^{-1}\frac{\omega L}{R}$ (31)

then $\sin\phi = \frac{\omega L}{\sqrt{R^2+\omega^2L^2}}$ and $\cos\phi = \frac{R}{\sqrt{R^2+\omega^2L^2}}$ (32)

Substituting the values from (30) (31) and (32) in equation (29) and dividing both sides of (29) by

we get

$$i = \frac{E_o}{Z} \sin(\omega t - \phi) + C\epsilon^{-\frac{rt}{L}} \qquad (33)$$

After t becomes large in comparison with $\frac{r}{L}$ the exponential term becomes so small as to be negligible, and the current reaches the permanent value expressed by the harmonic term.

The integration constant C is determined from the limiting conditions of our problem. Assume that the switch is closed at time $t = t_1$, when the instantaneous value of the e.m.f. is equal to $E_o \sin \omega t$. Since it is impossible to establish a current in an inductive circuit instantaneously then for $t = t_1$ $i = o$. Substituting these values in equation 33, we get

$$0 = \frac{E_o}{Z} \sin(\omega t_1 - \phi) + C\epsilon^{-\frac{rt_1}{L}} \qquad (34)$$

hence

$$C = -\frac{E_o}{Z} \epsilon^{\frac{-rt_1}{L}} \sin(\omega t_1 - \phi) \qquad (35)$$

Substituting this in (33), we get the complete

solution of our equation

$$i = \frac{E_0}{Z}\left[\sin(\omega t-\phi) - \epsilon^{-\frac{r}{L}(t-t_1)} \times \sin(\omega t_1-\phi)\right] \tag{36}$$

We can thus see that the current following the closing of an inductive circuit consists of two components; the permanent value expressed by the harmonic quantity, and the transient current, expressed by the exponential term.

To facilitate the discussion of equation (36) let us further simplify it

Let $\omega t = \theta$ and $\omega t_1 = \theta_1$

The exponential term then becomes.

$$\epsilon^{\frac{r}{L\omega}(\theta-\theta_1)}$$

and since $L\omega = x$, we can then write equation (36) in the form

$$i = \frac{E}{Z}\left[\sin(\theta-\phi) - \epsilon^{-\frac{r}{x}(\theta-\theta_1)} \sin(\theta_1-\phi)\right. \tag{37}$$

We can thus see that the greater r and the smaller x, the more rapidly the transient term disappears. The transient term also disappears completely if ($\theta_1 - \phi$) $= 0$ that is, when the permanent current passess through zero.

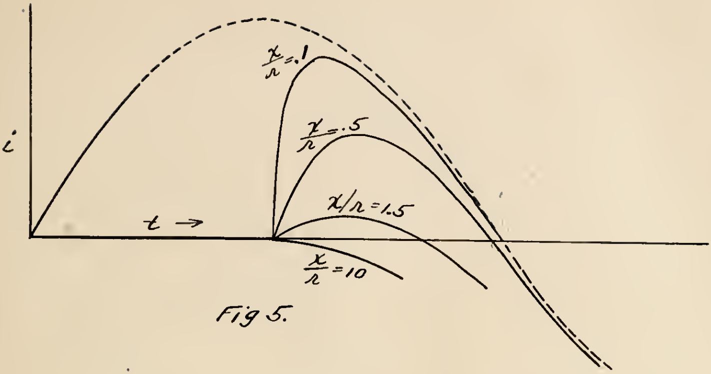

Fig 5.

In fig 5 the permanent value of the current is shown dotted. The heavy lines show the transient condition of the current for different values of x and r under the maximum condition, that is, when $(\theta_1 - \phi) = \frac{\pi}{2}$. In the case when several waves pass before the circuit approaches a permanent condition.

In fig 6 we have plotted the current when closing the circuit 0 30° 60° 90° 120° 150° behind the zero value of the steady current.

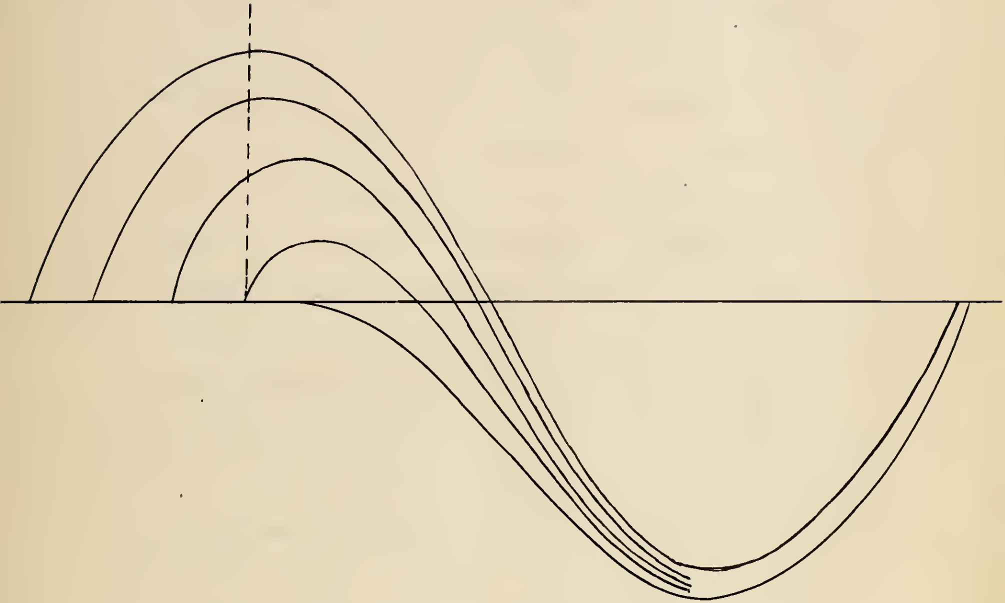

Fig. 6

ELECTRIC WAVES.

Before attempting to study the production and behavior of electric waves along wires, we will first make a preliminary inquiry into the characteristics of wave motion in general.

If a person standing on the shore of a quiet pond throws a stone into the pond, he will note that a surface disturbance, consisting of alternate ridges and hollows, will be propagated outward in uniformly expanding circles. If any light objects, such as a piece of cork or of paper were previously distributed on the surface of the pond, one will note that they will rise on the approaching wave, ride on the crest of the wave for a short distance, fall back into the succeeding hollow, to move again forward and upward on the next crest. These particles then describe circular or eliptical orbits. Since these particles are so light that they follow the movement of the water particles, we can then infer that the water as a whole does not move with the

movement of the waves, but that the waves are due to the periodic disturbances of the particles from their positions of equilibrium.

In the behavior of the water waves we have the illustration of the fundamental characteristics of wave motion in general.

1) All parts of the medium reached by the disturbance are subject to periodic displacements about their positions of equilibrium.

2) The disturbance is propagated at a uniform rate, each displaced particle transferring its motion to its neighbor by pressure or through some mechanical connection.

The moving elements possess kinetic energy due to their motion and potential energy due to their displacement, hence, wave motion also implies a flow of energy along with the waves.

EQUATION OF WAVE MOTION.

Let $y = f(x)$ tc the equation of the curve representing the water surface in fig. 10,

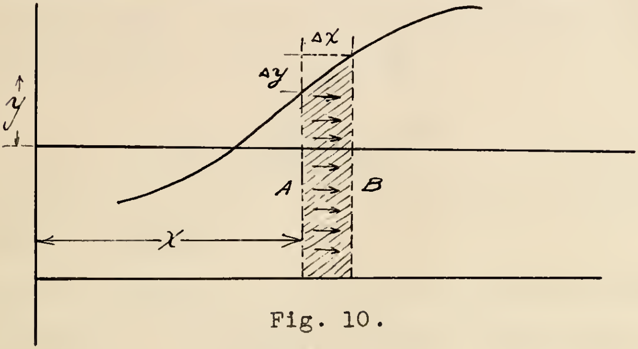

Fig. 10.

x = abscissa measured from any chosen origin,

y = ordinate measured from the normal water lever,

ρ = density of the water,

g = acceleration of gravity,

b = breath of the canal,

Δx = the thickness of the element AB

D = Normal depth of water in the canal, large in comparison with y.

The difference of level between the faces A and B will be $\frac{dy}{dx}\Delta x$, hence the excess of hydrostatic

pressure of face B will be

$$\Delta p = \frac{dy}{dx} \Delta x g \rho \qquad (51)$$

Hence the force which is pushing the element AB will be equal to this pressure multiplied by the cross-section of the canal Db.

$$\text{force} = \frac{dy}{dx} \Delta x g \rho Db \qquad (52)$$

The mass of the slice = its volume x its density, or

Mass = $Db \Delta x \rho$

Since we assumed the slice to be moving with the velocity v, its acceleration must then be equal to

$$dv/dt$$

Writing now force = mass x acceleration,

$$\frac{dy}{dx} \Delta x g \rho Db = -Db \Delta x \rho \frac{dv}{dt} \qquad (53)$$

The negative sign was placed in the equation for the reason that when Δh and Δx are both positive (as in fig. 10) the slice is in reality retarded in other words has negative acceleration.

Simplifying equation (53) by cancellation, we get

$$-g \frac{dy}{dx} = \frac{dv}{dt} \qquad (54)$$

$\frac{dy}{dt}$, being the rate of change of y with respect to t, is the rate at which the water in the slice is rising. Let time go on for interval Δt ; then

$$\frac{dy}{dt}\Delta t = \text{actual rise in time of the water level of the slice.} \qquad (55)$$

and $\frac{dy}{dt}\Delta t \cdot b\Delta x$ = volume of water (56) accumulated in the slice during time .

Since v is the velocity of the water at face A vDb is the flow per second across face A.

The volume flowing across B per second is

$$\left(v + \frac{dv}{dx}\Delta x\right)Db \qquad (57)$$

Therefore, in the interval Δt, there was accumulated in the slice, volume of water equal to

$$\left\{vDb - \left(v + \frac{dv}{dx}\Delta x\right)Db\right\}\Delta t, \text{ , or} \qquad (58)$$

$$-Db\frac{dv}{dx}\Delta x\,\Delta t \qquad (59)$$

Equations (56) and (59) are expressing the same thing, that is, the volume of water accumulated in slice AB during the time Δt

Hence we can equate them.

$$\frac{dy}{dt}\Delta t.\, b\Delta x = -Db\cdot\Delta x\cdot\Delta t\,\frac{dv}{dt} \qquad (60)$$

Cancelling same terms on both sides we get

$$\frac{dy}{dt} = -D\,\frac{dv}{dt} \qquad (61)$$

Differentiating equation (54) with respect to t, we get

$$\frac{d^2v}{dt^2} = -g\,\frac{d^2y}{dx\,dt} \qquad (62)$$

Differentiation equation (61) with respect to x

$$\frac{d^2y}{dt\,dx} = -D\,\frac{d^2v}{dx^2} \qquad (63)$$

Substituting in (62) from equation (63) we get

$$\frac{d^2v}{dt^2} = gD\,\frac{d^2v}{dx^2} \qquad (64)$$

Again by differentiating equation (54) with respect to x and equation (61) with respect to t and substituting, we get,

$$\frac{d^2y}{dt^2} = gD\,\frac{d^2h}{dx^2} \qquad (65)$$

In Dr. Franklin's book on electric waves we find the solution of equation (65). It is made up of the sum of any single valued functions of ($x+\sqrt{gD}\,t$) and ($x-\sqrt{gD}\,t$). Hence we can write

$$y = F(x-\sqrt{gD}\,t) + F(x+\sqrt{gD}\,t) \qquad (66)$$

Any function such as F ($x - \sqrt{gD}\,t$) represents a wave of wave shape y = F (x) travelling forward with velocity V = $\sqrt{gD}$. For the function F ($x-\sqrt{gD}\,t$) has the same value if we substitute $x - x_1$, for x and $t-t_1$ for t, as long as $\frac{x_1}{t_1} = \sqrt{gD}$

Any function of x such as y = f (x) represents a stationary curve whose ordinate y at any point is some function of x. It therefore represents wave form. If the curve moves bodily forward without a change of shape with a speed V then the ordinate having the value yfat the time t corresponding to the abscissa x has the same heigth as the ordinate y at a distance $x + dx$ corresponding to the time $t + dt$ provided dx/dt = velocity of the wave, the same state is repeated at a distance dx ahead at the time dt ahead. This is the characteristic of wave motion and holds equally true for disturbances in material medii as well as for immaterial waves.

THE ELECTROMAGNETIC MEDIUM.

When Young has conclusively shown that light is an undulatory motion, it was found necessary to postulate the existance of some medium of some medium of some kind, in which these undulations are propagated. Hence scientists have assumed the existence of the universal ether. Since light is now regarded as electromagnetic wave motion of very short wave-lenght, we then again assume the ether to be the medium of our electromagnetic action. When two magnetic poles are placed in air, the force of attraction or of repulsion does not change when we exhaust the air; it will be the same in the best vacuum obtainable, as it is in air. Since it is difficult to concieve of a "body action where it is not" we turn to ether as the medium through which our electromagnetic action takes place.

In recent years such evidence has been gathered which indicates that the chemical atom is an entity in itself, but that it is built up of minute charges of positive and negative electricity.

The negative electrical charges have been investigated, and shown to be composed of negative indivisible corpuscles, which were called electrons.

The electron has been isolated, and its mass and charge determined. Its mass is about 1/1800 that of a hydrogen atom; and its charge about 1.3×10^{-20} electromagnetic units. This charge is now assumed as being distributed over the surface of a sphere whose diameter is about 100,000th part of the diameter of a chemical atom. The hypothesis has been advanced that the electron itself is a strain center or focus of certain lines of strain in the universal ether. Hence the movement of electrons can be looked upon as a displacement of the strain form from one place to another in the ether. An electron then is a center on which converge the lines of electric force. The phenomena of electromagnetism prove that in the neighborhood of electrified bodies there is a distribution of electric strain, which is physical state of the dielectric or of the interpenetrating

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R. A. Millikan, Philosphical Magazine 1910 P.209.

ether, and in the neighborhood of magnetic poles, or conductors carrying the current, there is a distribution of magnetic flux.

The magnetic flux and electric force are then particular states of matter or of ether occupying the field and are vector quantities, having direction as well as magnitude at each point in the field.

The magnetic or electric attraction or repulsion can be explained by assuming that the lines exert a tension like stretched rubber bands, always tending to make themselves as short as possible, and at the same time exerting a lateral pressure, their arrangement in the field being the result of the conflict between their longitudinal tension and lateral pressure.

The Faraday's Law of Electromagnetic Induction states that if laws of magnetic flux move laterally through a dielectric they give rise to lines of electric strain in a direction at right angles to the lines of flux andto the direction of their motion. In the case of a

conductor it is the well-known statement that an e.m.f. is induced by the movement of the lines of magnetic flux.

Let L = lenght (in cins.) of a bar of conducting material

B = density of lines

V = velocity of the conductors with respect to the lines.

then E. M. F. = BLV in absolute units (67)

or E.M.F. = $BLV \cdot 10^{-8}$ in electromagnetic units (68)

E = E.M.F. per unit lenght = E.M.F./L (69)

Now we will turn our attention to the less known law of the production of the lines of magnetic flux by moving electric charges. This has been first demonstrated experimentally by Rowland in 1876 and confirmed in la~~t~~ter years by various experimenters. His experiment was as follows:

A pair of circular glass plates was covered with sectors of gold leaf. These sectors were charged to a high potential with electricity and set to a rapid rotation round their axis.

Between the two plates was suspended a sensitive shielded magnetic needle. It was found that when the charged plates revolved at a high speed the needle was deflected in the same manner as if electric currents were flowing in circular circuits concentric with the axis of rotation. If the plates were charged positively the convection current, as it was called, had the same magnetic effect as a galvanic current flowing around in the direction of rotation and if charged negatively, in the opposite direction.

From the above it follows that lines of electric strain moving transversely to their own direction create lines of magnetic flux. This can be represented by the formula:

$$H = KEV \tag{70}$$

where H is the magnetic force produced by the motion K the dielectric constant of the medium, and V the velocity of the lines parallel to themselves.

Let us now define D, as the number of electrostatic lines per square centimeter it

corresponds to B, the number of lines per unit area in the magnetic field

Let Q = charge inclosedin a sphere of radius r

the D = $Q/4\pi r^2$

Let k = dielectric constant

then the electric force at r = Q/kr^2

Dividing the electrical strain by the electric force

$$\frac{\frac{Q}{4\pi r^2}}{\frac{Q}{kr^2}} = \frac{4\pi}{k},$$ the electric elasticity. (71)

Let us next consider the relation between the magnetic flux and the electric strain.

By definition we have

$$B = \mu H, \quad \text{and} \qquad (68)$$

$$D = \frac{E}{\text{El. Elasticity}} = E\frac{k}{4\pi} \qquad (69)$$

by Rowland's experiment, we have

$$H = KEV \qquad (70)$$

Substituting the value of equation (69) in (70) we get $H = 4\pi DV$ (71)

where V is in a direction at right angles to the direction of the lines.

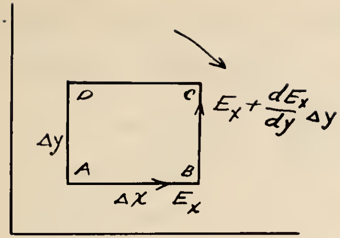


Fig. 11.

Imagine a small area of an electric field, such as a rectangle with sides dy and dx and let the electric force E at the center of that area be resolved into components E_x and E_y, parallel to dx and dy respectively.

Let us now obtain the line integral of the force round the area. We will go around in the direction of the arrow and multiply the lenght of each side by the component of the electric force in its direction, taking the products as positive when the force is in the direction of motion, and as negative when it is in the negative direction, and finally we will obtain the algebraic sum of all these products.

The work along AB is $-E_x \Delta x$

along BC it is $\left(E_x + \frac{dE_x}{dy}\Delta y\right)\Delta x$

along CD it is $E_y \Delta y$

and along DA it is $-\left(E_y + \frac{dE_y}{dx}\Delta x\right)\Delta y$.

Hence going around the area we get

$$-E_x\Delta x + \left(E_x + \frac{dE_x}{dy}\Delta y\right)\Delta x + E_y\Delta y - \left(E_y + \frac{dE_y}{dx}\Delta x\right)\Delta y$$
$$= \left(\frac{dE_x}{dy} - \frac{dE_y}{dx}\right)\Delta x\,\Delta y \qquad (72)$$

The above line integral is the electromotive force acting round the area and the quantity in the brackets is called the curl of the electromotive force and is written : Curl E. If there is a magnetic force H in a direction z at right angles to the plane xy, then the total magnetic flux through the area $\Delta x\,\Delta y$, or the number of lines of electric force passing through the area is $\mu H\Delta x\Delta y$. If the e.m.f. is due to the variation of this field, we have

$$\left(\frac{dE_x}{dy} - \frac{dE_y}{dx}\right)\Delta x\,\Delta y = \frac{d}{dt}\left(\mu H\,\Delta x\,\Delta y\right) \qquad (72)$$

$$\text{Curl E} = -\dot{H}\mu \qquad (73)$$

We can now obtain an expression for the curl of the magnetic force in a similar fashion. Resolving H into two components, we obtain, as in the case of electric force, the expression

$$\text{Curl } H = \left(\frac{dH_x}{dy} - \frac{dH_y}{dx}\right) \qquad (74($$

Let D = electric displacement normally through the area $\Delta x \Delta y$ drawn in the magnetic field the time rate of change of this displacement being the displacement current $\frac{dD}{dt}$ the displacement current produces the same magnetic effect as ordinary galvanic current, the distinction between the two being quite artificial. The line integral of magnetic force round the area is equal to 4π times the total current through the area.

Hence, we can write

$$\left(\frac{dH_x}{dy} - \frac{dH_y}{dx}\right)\Delta x \Delta y = 4\pi \frac{dD}{dt} \Delta x \Delta y \qquad (75)$$

But above we have shown that

$$KE = 4\pi D$$

Hence, substituting this in eq. (74) and writing Curl H for the quantity in parenthesis on left side of eq. (75), we get

$$\text{Curl } H = K \dot{E}. \qquad (76)$$

where $\dot{E}$ stands for the time variation of E

E and H are both at right angles to a common direction taken as the X axis and vary in that direction alone, that the propagation is

in that direction we have for the curl equations from (76)

$$\frac{dH}{dx} = -K\frac{dE}{dt} \qquad (77)$$

and from (73)

$$\frac{dE}{dx} = -\mu\frac{dH}{dt} \qquad (78)$$

Differentiating both sides of equation (77) and (78) with respect to x and t, we get

$$\frac{d^2H}{dx^2} = K\mu\frac{d^2H}{dt^2} \qquad (79)$$

$$\frac{d^2E}{dx^2} = K\mu\frac{d^2E}{dt^2} \qquad (80)$$

These equations are similar to those deduced for water waves in the first part of this section. The general solution is $H = f(x-vt) + F(x+vt)$ and $E = f(x-vt)\ \ F(x+vt)$ by differentiating the value of E and H twice with respect to t and twice with respect to x and substituting in (79) and (80) we get for $v = 1/\sqrt{ku}$ The expressions $f(x-vt) + F(x+vt)$ are general expressions for wave motions along x, one in the positive and the other in the negative direction.

For, after a given interval of time $t_{,}$, the expression $f(x-vt)$ becomes $f(x-vt-vt_{,})$ and if the origin be moved forward along OX by the distance $vt_{,}$ the abscissae refrred to the new origin being $x_{,}$, then $x = x_{,} + vt_{,}$. The expression for the disturbance is then $f(x_{,} + vt_{,} - vt - vt_{,}) =$ $f(x_{,} - vt)$; in other words, referred to the new origin it has the same form as it had when referred to the old origin at a time t, earlier. Its form is therefore the same, and it has moved forward with velocity V

Another very important fact remains to be noted. That is from the equations (79) and (80) and their general solutions, we see that the electrical and magnetic fields which compose the wave, are in phase. We can think of the two fields as mutually sustaining each other in their sidewise motion. The magnetic field may be though of as inducing and thereby sustaining the electric field. according to the law of induced electromotive force. The moving electric field may be thought of as inducing and thereby sustaining the magnetic field,

according to the law of induced magnetomotive force, which, as I explained above, was demonstrated experimentally by Rowland.

When the lines of force are created at one point in the dielectric they travel through it with the velocity $1/\sqrt{ku}$, and as they move they give rise to lines of magnetic flux at right angles to themselves and to the direction of motion. If magnetic lines are created at any point, they diffuse through space with the same velocity, their motion giving rise to the lines of electric force. If the waves are on transmission lines, the same action takes place, the conductors simply giving direction and guiding the disturbance.

Let us now take the case of an alternator suddenly connected to a pair of long wires. For simplicity sake let us assume the wave shape of the electromotive force of the alternator to be rectangular. This wave of e. m. f. can then be represented as in fig. 12.

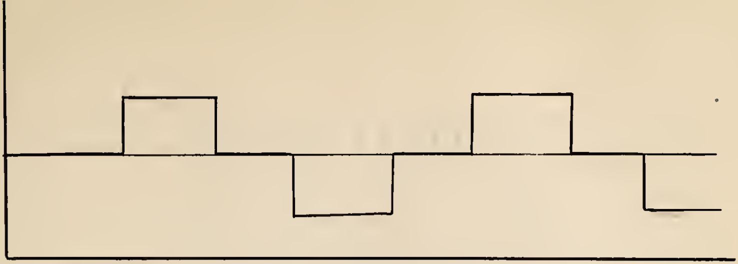


Fig. 12.

As the e.m.f. suddenly rises at one end of the wires there is established an electric force between the wires; this electric force then diffuses with a certain speed. The distribution of the electric force is shown in fig. 13 by the full lines.

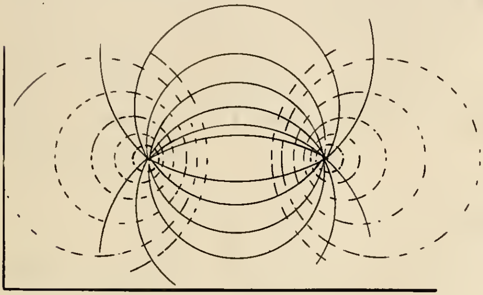


Fig. 13.

A side view is shown in fig. 14. The movement of the electric field implied a movement of the electric charges, since the lines are thought of as terminating on electric charges. This movement of electric charges is accomplished by an electric current as shown in fig. 14.

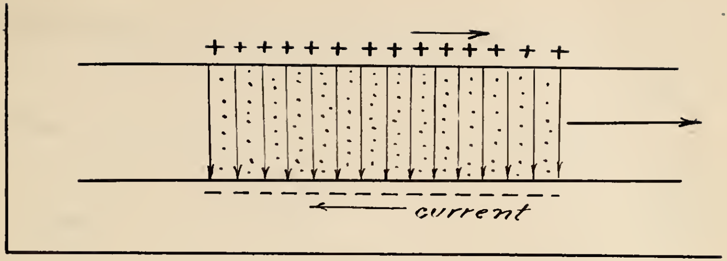


Fig. 14.

This electric current then creates lires of magnetic flux, direction of which is perpendicular to the direction of the dielectric flux and to the direction of motion. These magnetic lines are shown dotted in figures 13 and 14. Infig. 14 their direction between the wires is away from the reader.

Let the value of the magnetic lines of force per cubic centimeter be H and the value of the electric lines per cubic centimeter be E. Let v $\doteq$ velocity of propagation of the electric wave. Then the value of the electric lines created by the movement of H magnetic lines is,

$$E = \mu H v \tag{81}$$

and the value of the magnetic lines created by the

the movement of the electric lines E is,

$$H = k E v \qquad (82)$$

Also from definitions of B and D we have,

$$B = \mu H \qquad (83)$$

and

$$D = k E \qquad (84)$$

In almost any book on elementary electricity and magnetism, we find it demonstrated that the energy in a cubic centimeter of electric occupied by electric lines is $\frac{1}{2} D^2/K$ and the energy per cubic centimeter of magnetic flux is $\frac{1}{2} B^2/\mu$. Substituting from equation 83 and 84, we find that

$$\tfrac{1}{2} K E^2 = \tfrac{1}{2} \mu H^2 \qquad (85)$$

or that the energy associated with a pure wave is equally divided between the electrostatic and the electromagnetic components. Hence as soon as the dielectric lines begin to move freely they have to part with some of their energy which then streams into the magnetic field. If either set of the lines disappear, either by meeting an open end of the line, or a dead short-circuit, the energy

will surge back into the remaining set, which will then become of doubled intensity.

Whatever may be the wave-shape of the pulse, we can express it as a sum of harmonic terms also to use such quantities as we are more familiar with, we will in what follows,
substitute voltage v for the expression of electric displacement D, and current for the magnetic flux, since

$$\text{voltage} \propto D$$

$$\text{current} \propto H$$

Since an electromagnetic wave is generally a sine wave we can then express an electric wave as:

$$e = e_0 \sin(\phi \mp \omega) \tag{86}$$

$$i = i_0 \sin(\phi \mp \omega) \tag{87}$$

where ω is the distance angle and ϕ the time angles, i_0 and e_0 the maximum values of current and voltages, respectively. When using the ideas of current and voltage, we have shown in the first section that the electrostatic energy of a circuit, or a section of a circuit, having a capacity C and the

voltage between the lines e is

$$\frac{1}{2} C e^2$$

and the electromagnetic energy of a circuit, or a section of a circuit having an inductance L and current flowing i is,

$$\frac{1}{2} L i^2$$

From the preceding discussion we know that in a pure wave the electrostatic energy must be equal to the electromagnetic energy. Hence

$$\frac{1}{2} L i^2 = \frac{1}{2} C e^2 \qquad (88)$$

or

$$\frac{e}{i} = \sqrt{L/C} \qquad (89)$$

this expression is the same as that of equation (85) excepting that in (88) we use current and voltage, which no doubt are more familiar to the engineer.

In fig. 15 are shown two rectangular electromagnetic waves travelling in apposite directions along a transmission line. When they begin to overlap, the two fields are of course adding algebraically. We can then see that at the overlapping parts the magnetic field is zero.

and the electric field of doubled intensity. When the two waves are completely superimposed, the

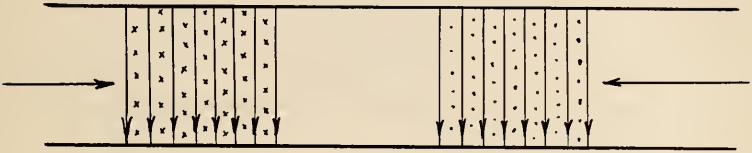


Fig. 15

state of affairs is shown in fig 16; the magnetic field is everywhere zero and the electrostatic field is of doubled intensity

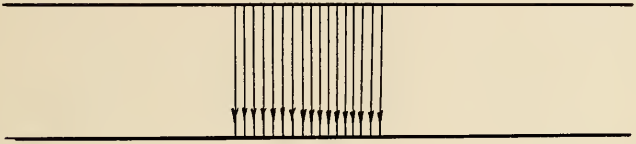


Fig. 16.

In fig. 17 and 18 we have a similar case, where, however, the superimposition

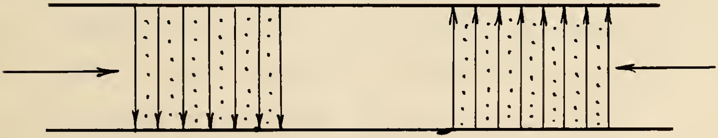


Fig. 17

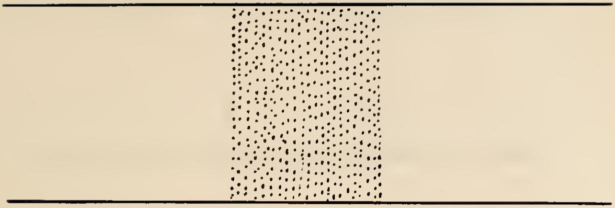


Fig. 18.

gives a field of doubled magnetic intensity.

Let us now consider the phenomena occuring when an electromagnetic wave reaches the end of a line.

First we will consider the case where the end is open or insulated. When the lines of electric force arrive at the end of the line they can not proceed farther because their ends cannot be detached from the conductor, but their inertia causes them to travel as far as they can by stretching themselves; hence as they reach the end of the line they extend themselves as shown in fig. 19. As soon however, as they come to rest, the accompanying magnetic flux, which is produced only

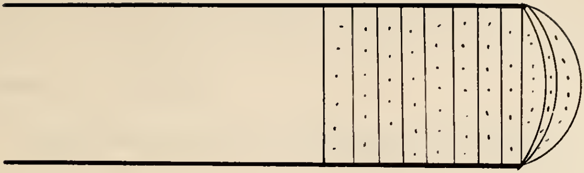


Fig. 19.

by the sidewise motion of the dielectric lines, vanishes; but its disappearance results in the creation of additional dielectric lines to conserve the energy. Some of the dielectric lines are then in a state of extra stretch, but owing to their longitudinal tension they tend to contract and to start the whole mass of dielectric lines back again. As soon, however, as the lines begin to travel their motion recreates the magnetic flux lines, and part of the electric strain lines vanish to supply the magnetic energy. Then the wave is re-established and runs back again to the origin. Here it may be reflected again and so travel backwards and forwards until its energy is

dissipated. If the receiving end of the cable is short-circuited then the process of reflection is somewhat different.

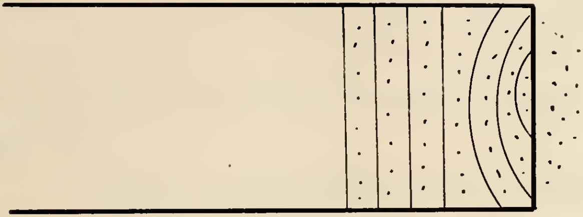


Fig. 20.

When the dielectric lines arrive at the end their ends follow on round the short-circuit and the dielectric lines therefore tend to shrivel up to nothing as shown in fig. 20. But this process implies a movement of each part of the dielectric line at right angles to itself and so gives rise to a line of magnetic flux embracing the end conductor, which is left behind as the equivalent form of energy when the dielectric lines disappear. Hence when the wave reaches the closed circuit end all the dielectric lines vanish for the moment and are replaced by lines of magnetic flux.

But this condition is not stable. The closed magnetic lines embracing the short circuit end begin to expand outwards, due to their lateral pressure, and as their motion begins dielectric lines are recreated and the energy is again equally divided between the dielectric and the magnetic component.

From the above reasoning we can then formulate two laws as regards the reflection of electromagnetic waves:

1) When an electromagnetic wave is reflected from the open end of a transmission line the magnetic component (and hence the current) is reversed, but the electric phase (voltage is not reversed.

2.) When an electromagnetic wave is reflected from the short-circuited end of a transmission line the voltage is reversed, but the current is not reversed.

If the receiving end is not perfectly insulated or perfectly short-circuited, the energy

of the wave is partly reflected and partly transmitted and the resulting condition becomes quite complicated. If at any parts of the transmission line the capacity or inductance are greater than at the other parts, these lumps of capacity or inductance will cause partial reflections of the wave, and the resulting condition of oscillations will be still more complicated.

Let us now take the case of an electromagnetic wave started by the sudden switching of a generator on the line. When the wave reaches the resistance at the receiving end it is partly reflected. Let e, be the voltage across the transmission line and i, the current in the line, which are associated with the outgoing wave and let e and i associated with the reflected wave. Since we are dealing with a wave pulse we know that the energy of the wave is equally divided between the electrostatic and the electromagnetic components.

then $$\tfrac{1}{2} L i_1^2 = \tfrac{1}{2} C e_1^2 \qquad (90)$$

and
$$\tfrac{1}{2} L i_{,,}^2 = \tfrac{1}{2} C e_{,,}^2 \qquad (91)$$

$$\frac{e_{,}}{i_{,}} = \pm\sqrt{\frac{L}{C}} \qquad (92)$$

and
$$\frac{e_{,,}}{i_{,,}} = \pm\sqrt{\frac{L}{C}} \qquad (93)$$

We will take the positive sign in equation 92. According to the right hand rule we know that when the diredtion of travel of the wave is reversed, either e or i must be reversed but not both. Since we took the positive sign in eq. (92) we must write eq. (93) as

$$\frac{e_{,,}}{i_{,,}} = -\sqrt{\frac{L}{C}} \qquad (94)$$

The total current at the end of the line in other words the current entering the receiving circuit is $(i_{,} + i_{,,})$ and the total voltage across the end of the line is $(e_{,} + e_{,,})$.

If the inductance and the capacity and inductance of the receiving circuit are small in comparison with the resistance, we can write without an appreciable

error, that

$$i_{,} + i_{,,} = \frac{e_{,} + e_{,,}}{R} \tag{95}$$

Keeping in mind that there is a fixed ratio between the current and the voltage of an electromagnetic wave (see eq. 92 and 93) we can at once understand three special cases of reflection:

A.) Open circuit end; then R = ; then from equation (95) $i_{,} + i_{,,}$ must be equal to zero, since $e_{,} + e_{,,}$ is a finite value. Now if $i_{,} + i_{,,}$ is zero, $i_{,} = - i_{,,}$; that is we have a reflection of the current. Since the direction of the wave is in opposite direction, only one of the two factors current or voltage must be reversed. This follows from the right hand rule.

B.) Short circuited end; then R = o From equation (95) $e_{,} + e_{,,}$ must be zero, since $i_{,} + i_{,,}$ can not be infinite. Now if $e_{,} + e_{,,} = 0$, $e_{,} = - e_{,,}$ In other words, when the wave is reflected the current is in the same direction, but the voltage between the wires associated with the waves is reflected.

C.) Let the receiving end be of a resistance equal to $\sqrt{\frac{L}{C}}$

Substituting this in equation 95 we get,

$$i_{,}+i_{,,} = \frac{e_{,}+e_{,,}}{\sqrt{\frac{L}{C}}}$$

But $\quad i_{,} = \frac{e_{,}}{\sqrt{L/C}}$

hence $i_{,,} = o$ and $e_{,,} = o$

that is, no reflection takes place, but all of the energy associated with the wave is absorbed in the receiving circuit.

In his book on transient phenomena Dr. Steinmetz shows that a travelling wave can be represented by equations

$$i = i_{o}\,\epsilon^{-ut} \cos(\phi \mp \omega - y) \qquad (96)$$

$$e = e_{o}\,\epsilon^{-ut} \cos(\phi \mp \omega - y) \qquad (97)$$

The power can be obtained by multiplying equation (96) by (97)

$$p = e_{o} i_{o}\,\epsilon^{-2ut} \cos^{2}(\phi \mp \omega - y) \qquad (98)$$

expressing cos as a function of double angle

C. P. Steinmetz: Transient Phenomena and Oscillations. McGraw Hill.

we get,

$$p = \frac{e_0 i_0}{2} \epsilon^{-2ut} \left[1 + \cos 2(\phi \mp \omega - y) \right] \qquad (99)$$

u in the above equations is called the attenuation constant. It has the same significance here as in the first section of this thesis where single energy transients were discussed. It represents the rate at which the power of the wave is being dissipated. ϕ is the time angle, ω the distance angle and y is the phase angle the value of simply determines the initial value of the voltage and the current, which then become

$$e = e_0 \cos y \qquad \text{and} \qquad (100)$$

$$i = i_0 \cos \gamma \qquad (101)$$

In equation (99) we see by inspection that the power consists of two components; one is a oscillating component with double frequency the other is a steady flow of power

$$\frac{e_0 i_0}{2} \epsilon^{-2ut} \qquad (102)$$

This always occurs when a quantity of energy is impressed on the circuit, This may happen in a

number of ways; such as lightning stroke, switching, momentary short-circuit, etc. Such energy is then gradually distributed and dissipated over the circuit by a travelling wave.

Circuits which are used industrially never have the same dissipation constant throughout their lenght. This follows from the

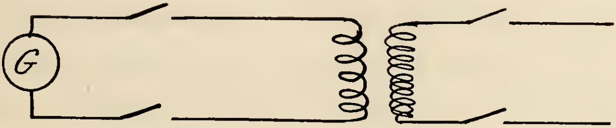


Fig. 21.

dissipation constants which are $\frac{r}{L}$ in an inductive circuit and $\frac{g}{C}$ in an anti-inductive circuit. Take for instance such circuit as shown in fig. 21. Let the power supply be cut off; we then have $\frac{1}{2}Li^2$ magnetic energy and $\frac{1}{2}Ce^2$ dielectric energy stored in the circuit. This energy is dissipated by a transient whose duration is given by Dr. Steinmetz as $\frac{1}{2}\left(\frac{r}{L}+\frac{g}{C}\right)$ In the transformer the energy is large and the dissipation

constant $\frac{r}{L}$ small; hence the time occupied before the transient woulddie down to a small value would be perhaps several seconds. In the line, on the other hand, r is fairly large and L small; then in the line the transient would be of a very short duration. But the line and the transformer are connected together, hence the oscillation in the transformer and the oscillations in the line must die down simultaneously. The transient in the compound circuit must then be accompanied by a power transfer, from the transformer to the line, by a travelling wave.

STANDING OSCILLATIONS.

When electric waves are relected their interference with advancing waves may create standing oscillations on the line. Their production is exactly analogous to the production of standing waves in stretched strings or organ pipes. The energy surges from the magnetic to the dielectric, back again, and so on. It also decreases by a transient according to the logarithmic law as explained in the first part of this thesis.

Since it is the same energy that surges between its two forms, we have

$$\frac{1}{2} L i_0^2 = \frac{1}{2} C e_0^2 \qquad (103)$$

Solving equation (103) we get

$$\frac{e_0}{i_0} = \sqrt{\frac{L}{C}} = Z_0 \qquad (104)$$

the quantity Z_0 is called the surge impedance of the circuit.

The relation is very important as frequently we have one of the quantities given and we wish to gain some idea as to the magnitude of the other.

For instance if a line is short-circuited and the short-circuit suddenly broken, the voltage induced will be equal to $e_o = iZ_o$. If again a dead short-circuit occurs on the line the current which will surge through the short-circuit is determined by the relation $i_o = \frac{e_o}{Z_o}$ where e is the line to line voltage. If a lightning strikes the line the maximum voltage e_e is determined by the disruptive strenght of the insulation again momentary over-voltages, while the current will be $i_o = \frac{e}{Z_o}$

In a high potential transformer the inductance is high, but the capacity comparatively low, hence Z_o is high. In such a case a high transient voltage can produce only a moderate transient current, In a cable the reverse of the above is true. There we have large oscillating current accompanied by comparatively low surge voltages. Thus we see that reactive apparatus can be damaged by a disturbance originating elsewhere, where it was perhaps harmless, but built up excessive voltage upon entering the

reactive apparatus. The simple consideration of the values of Z_0 in the different portions of the circuit can give us considerable information on the relative danger that one part of the system is to the other; it also reveals the reason while a transformer is so susceptible to damage by surges and oscillations.

CUMULATIVE AND CONTINUAL OSCILLATIONS.

In one of the previous sections we have defined a transient as a phenomenom by which the stored energy of the circuit adjusts itself to the change in the circuit conditions. A change in the circuit conditions generally involves a change in the amount of the stored energy. The difference between the amounts of stored energy, required before and after a change, usually oscillates between the magnetic and dielectric energy. In as much as there is a dissipation of energy accompanying such oscillations, in every circuit, the transient must die out, at a rate depending upon the constants of the circuit. Hence we can readily see that oscillations can become continual or cumulative, only if there is a steady supply of energy into the oscillating section. We can not then say that cumulative or continual oscillations are the result of energy readjustment, but must keep in mind that such oscillations are possible only if there is a steady supply of power

into the oscillating section.

If the power supplied is equal to the power dissipated the oscillations will become continual and of constant amplitude. If the power supplied is less than the power dissipated, then the oscillation will die down by a transient to a value at which the dissipation will equal the power supplied. If the energy supplied is greater than the energy dissipated, then the oscillations will become cumulative, and their amplitude will increase, either till the system breaks down, or till the increased dissipation will take care of all the energy fed into the oscillating section.

We can then define a cumulative or a continual oscillation as an energy and frequency transformation, from the low frequency or direct current energy to the high frequency energy of the oscillation. Then continuals oscillations may also cause an energy transformation to be brought about in the following way: A change in the circuit conditions produces a transient. This resulting transient may again produce a change of circuit

conditions, and another energy readjustment by a transient and so on.

Imagine a three phase three wire transmission line and let the voltage from line to line be, say 60,000 volts. The voltage from the line to the neutral will then be $\frac{60,000}{\sqrt{3}}$ volts = 34,600 volts. If now an insulator breaks, the ground may be brought close enough to the line to cause a spark-over. An arc will be established and the line will then discharge from 34,600 to the ground potential, while the other two lines will be charged from 34,600 volts to 60,000 volts, that is from the Y to the delta voltage, the energy being supplied by the power system. As soon as the faulty line discharges to the ground, the arc will cease and the circuit to the ground will open. The faulty line will then again be charged from the power supply of the system, and the other lines correspondingly lowered in potential (from 60,000 volts) till the voltage on the faulty line will be sufficient to spark to theground, and the whole

thing will be repeated again. The constants of the circuit are usually such as to make each discharge oscillatory. We then will have on our line continual oscillations.

In Figs 101 and 102 is shown such a series of successive or recurrent oscillations, resulting from an arcing ground on one phase of an isolated system consisting of 10 and 21½ miles respectively of 22.000 volt 3-phase 40 cycle circuit. In this case three transients occur during each half wave of voltage.

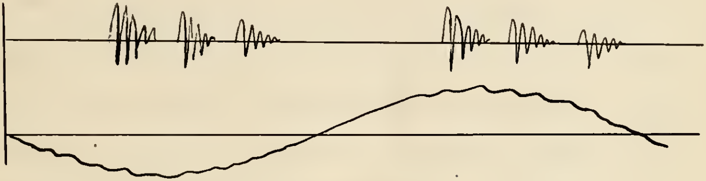


Fig 101

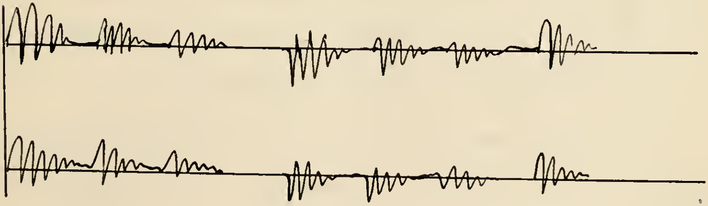


Fig 102

Fig 103 shows a reproduction of an oscillogram of an arcing ground oscillations on 32 miles of the same system. Here each transient oscillation persists up to the beginning of the next transient

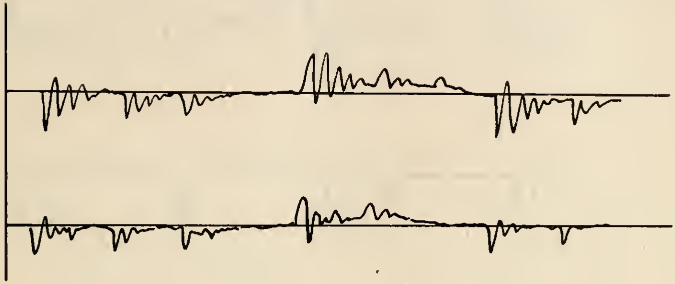


Fig 103

of the same half wave of circuit voltage, and the recurrent oscillations thus tend to run into each other and approach a continuous oscillation. When successive oscillations run into each other they naturally synchronize, as the first oscillation of the second train of oscillations would start at the maximum of the last oscillation of the first train.

The reproductions shown in fig 104 and 105 show the formation of a continuous oscillation by the overlapping of successive recurrent oscillations,

and finally figs. 106 and 107 show a continuous oscillation

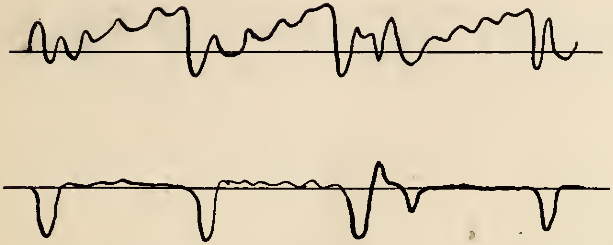


Fig 104

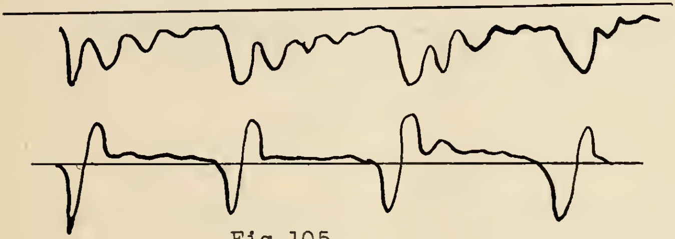


Fig 105

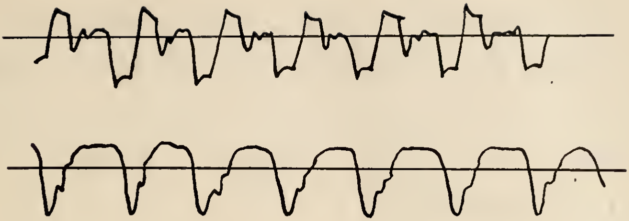


Fig 106

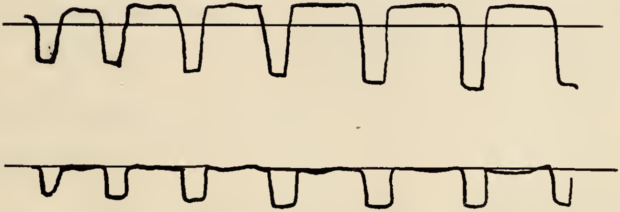
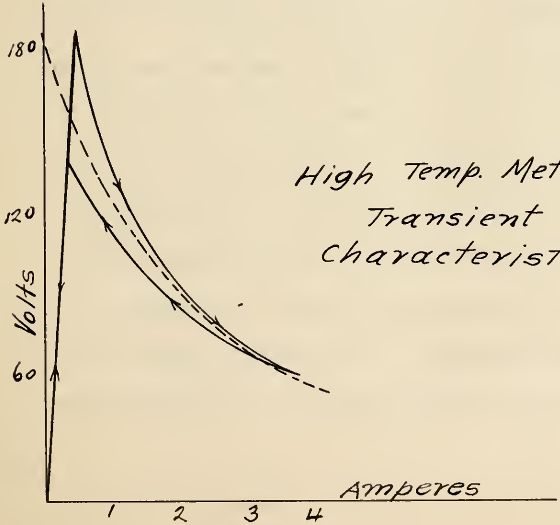


Fig 107

In figs. 104 and 105 the component recurrent oscillations are still noticeable by a periodical rise and fall of the amplitude of the wave, while in figs 106 and 107 the amplitude has become constant. These oscillations were taken on an artiticial transmission line and the results published by Mr. J. H. Cunningham in the A.I.EE.

of oscillations can start, and so on; In other words the dead period is necessary, in as much as during such a period the energy for the next oscillation is stored in the system. If, however, no dead period occurs, the energy for the oscillation; in other words, there must be such a lag in the oscillation, which gives a negative energy cycle, or reversed hysterisis loop. Such a reversed hysterisic cycle is then essential for the production of continual oscillations. The singing arc has such a characteristic as can be seen from fig 109. The dotted line represents the volt-ampere characteristics.



under stable operation, while the full lines show the same characteristic in the oscillating arc. The voltage for the full lin characteristics had a frequency of 60 cycles and was very nearly of the sine-wave shape.

In the hunting of synchronous machines we have an example of another form of continual or cumulative oscillation. The energy there surges between the kinetic energy of the moving part, and the magnetic energy of the synchronizing field. The energy is supplied by the negative hysterisis cycle between the synchronizing force and position displacement.

Such oscillations as shown in fig 101 are continual, since each train of oscillations dissipate the same energy, that is the stored energy of the system. Oscillation in which the energy supply is through a negative hysterisic cycle may, however, become cumulative. The area of the hysterisis loop becomes greater as the oscillating current and voltage increase. Since the energy supply is proportional to the hysterisis

loop, we can see that the energy supply increases with an increase in the intensity of oscillations.

The frequency of such oscillations usually the natural period of the circuit or a section of a circuit. It may also be some harmonic of the generator, if such a harmonic is sufficiently close to the natural period of the system.

The continual oscillations are considered the most dangerous disturbances. The lightning arrester affords little protection since the overvoltage is generally insufficient to cause a discharge over the lightning arrester. These high frequency oscillations, recurring perhaps for hours, weaken the insulation either by the sustained overvoltage or by the heating of the dielectric caused by the high frequency. An ordinary transient dissipates the energy stored in the system. A continual oscillation, however, involves an energy transformation from the power supply to the energy of the oscillation. The energy which gives these

oscillations their destructiveness is not limited, as in an ordinary transient, but is supplied continuously by the prime movers. Since an arc has no frequency of its own, but its frequency is determined by the constants of the circuit, a lightning, sudden switching, etc., is only the exciting cause to start the energy transformation from the power of the system to the high frequency oscillation, which is determined by the constants of the circuit.

In the last few years several devices have been developed to protect the transmission system against these continuous oscillations.

A full description of them, accompanied by a thorough discussion of the principle involved, can be found in another section of this thesis, dealing with the protective devices.

Lightning Arresters

The installation of lightning arresters is of the nature of an insurance. A certain percentage of the cost of the apparatus can reasonably be invested as a safeguard in protecting the apparatus. Furthermore, a percentage of the income can also be invested in protective apparatus as an insurance against interruption of service. The value of uninterrupted service depends upon the nature of the use of the current and will consequently vary in different plants. Plants which make contracts involving penalties for interrupted service naturally put a premium on good service. Protecting the insulation of the apparatus has been an easier matter than protecting the continuity of service.

The subject of the choice of an arrester for any installation is a broad one. The selection of an arrester for a particular case depends entirely on the local conditions, such as, the nature of the circuit to be protected, conditions on the line to be handled, geographical location,

and, as above mentioned, the nature of the penalty for interrupted service. As regards the line itself, we can select our apparatus for a specified voltage and power. But the conditions to be handled are variable. The phenomena with which we have to deal under abnormal pressure and frequency are of such complicated nature, both in respect to the size, length, and form of wave, and to the time and relative order of their occurrence, that it has hitherto been impossible to design a protective device which will meet all the requirements imposed upon it, for given conditions of voltage and energy flow of the system. The various devices in use are of value only under the conditions for which they are designed. Apparatus can be selected to suit the geographical conditions, that is, they can be built in proportion to the extremes of temperature. With regard to the continuity of service, the selection of arresters will vary. If interrupted service means a large penalty, more money can be invested in lightning protective apparatus.

However, in general, the best means we

have of selection of arresters is to watch their performance on previous installations. Some power companies advocate the advisability of having regular records kept of the results of periodical inspection with regard to maintenance and performance. If such a collection of data were at hand for each type of arrester on different installations, the problem would be greatly simplified.

Many forms of lightning arresters have been devised for high tension transmission lines. The discussion of different types will be limited, however, to those occurring most frequently in practice, as their constant use has brought out some noteworthy improvement.

The following types will be discussed:

1. Overhead ground wire,
2. Gap type arresters,
    a) Sphere gaps
    b) Impulse gaps
3. Choke Coils
4. Condensers
5. Multigap Arresters
6. Aluminum Cell Arresters
7. Oxide Film Arresters.

Overhead Ground Wire.

In the last few years there was a considerable variety of opinion among engineers regarding the utility and protective value of overhead ground wire. Some maintained that an overhead wire does afford protection against anything, but a direct stroke. Others again were of the opinion that the ground wire is far more troublesome than it is worth.

Ground wires are usually made of galvanized iron. The material does not make much difference, as long as we keep the resistance low enough. In order to have a low resistance, it seems well to use as heavy a wire as the economic consideration will permit. In order to improve the screening action it is better to use a greater number of wires of smaller cross-section, than a lesser number of heavier wires. The protection will then be better for the same weight of wire.

The usual method of installation is as follows: Three wires are generally employed, one

at the top of the pole or tower and one at each end of the cross-arm. They are generally tied to glass insulators, which, however, is done for mechanical reason, since the wires are grounded as often as possible, in order to keep the resistance to ground at a low value.

An external lightening can affect a circuit in three ways:

a) by a direct stroke,
b) by electromagnetic induction,
c) by electrostatic induction,

The first case seldom occurs, but when it does occur, no system of protection can prevent a damage to the circuit. In many localities where thunderstorms are frequent and violent, they attach iron rods, about 6 feet long and well grounded, to the top of the poles. These rods afford about the same degree of protection as ordinary lightning rods on buildings. Often, however, cases have been noted where the lightning struck the lines in the immediate neighborhood of such a rod. This statement

however, must not be construed as saying that such rods afford no protection whatever. Their principal function is to cause a silent discharge into the atmosphere, as so to relieve the electrostatic stresses in the neighborhood of the lines. So while they can not prevent a damage once the lightning struck the line wires, they greatly decrease the possibility of a direct stroke.

As to the second case, all that need be said is that electromagnetic induction is merely a theoretical possibility. The transient induced magnetically is generally of low energy content, and hence will not ordinarily cause any damage to the line insulation or to the station apparatus.

Electrostatic induction is what is necessary to protect the lines against. The transients induced by the electrostatic action of the clouds, the lightning, or the atmosphere, often reach destructive values. Hence we either must divert the transients so induced from the

lines to the ground by means of the lightning arrester, or else protect the lines against electrostatic induction by means of the overhead ground wire. Often we do both.

To explain the action of an overhead ground wire, let us consider the entire transmission system as a huge conductor, insulated from the earth. Suppose now that a positively charged cloud moves in the proximity of the wire. There will then be a negative charge induced on the line which we can think of as being the ends of the tubes of induction between the cloud and the line. This induction will set free a positive charge on the transmission system. This charge, being repelled by the cloud, will tend to pass to the earth. It may pass as a leakage current to the ground, or, if the approach of the cloud is rapid, and the leakage resistance high, the electrostatic stress established may be great enough to puncture the insulation and pass to the ground. A transient will then occur along the

line, which may cause damage to the reactive apparatus in the system. The intensity of the charge will in all cases depend upon the potential of the line wires due to the charge of the cloud. If now we have other wires in the proximity of the live wires, and these wires are grounded at frequent intervals, a similar action will occur, excepting that the free charge can find a ready, low resistance path to the earth. The "bound" charge will of course remain on these grounded wires. Under these conditions, the field inducing the charge on the line wires will no longer be the field due to the cloud alone, but it will be the resultant field of the positively charged cloud and the negative "bound" charge on the ground wires. In other words, the grounded wire will have the tendency of neutralizing, to a certain extent, the potential set up by the cloud. This action is very similar to the shielding action of the "Faraday's cage."

Assume now that we have no ground wire

along the transmission line. The line has gradually been charged oppositely to the cloud. If now the cloud discharges, the previously "bound" charge will be set "free", since the potential at the line with respect to the cloud will be zero after the lightning flash. This free charge will then cause a considerable rise of potential between the line and the ground. The energy of the charge will then be converted into a surge along the wire, and may cause puncturing of the insulation or other damage. If, however, a ground wire is present the potential between the ground and the line wire after the lightning flash, will be considerably less, since the impressed potential before the flash is less with the ground wires than without them.
If the charge on the grounded wires can not pass readily to earth the charge on them will tend to set free a negative charge on the line wires by the lightning flash. The worse condition would be that under which the charge on the grounded wires could not pass to the ground at all, in which case

the sum of the two charges on the line wires will be just equal to that which would have existed if there was no ground wire. The passage of the charge from the ground wire to the earth will always be more or less obstructed by the inductance of the path and will also be dependent upon the suddenness with which the cloud discharges.

Ralph D. Mershon has calculated approximately the shielding effect of ground wires. He shows that making reasonable assumptions the potential of the line wire due to an electrostatic induction from the cloud is only 30% of the value to which the potential would rise if the ground wire were not used. Assuming that the reduction in potential is only 50% we can see that the energy in the surge induced by the lightning is only ¼ of what it would be if the ground wire were not present, since the energy of a surge is proportional to the square of the voltage. The proximity of the grounded wire will also help to dampen out any high frequency surges due to the inductive action.

The line wire can be thought of as the primary of a transformer, and the ground wire as the short-circuited secondary. The loss of power under the normal operation of the line will be negligible due to the distance between the line and the ground wire (2 feet or more) and the low normal frequency.

Dr. Steinmetz[*] recommends that the ground wire be placed above the conductors in such a position that all the line wires are included in an angle of 60° below the overhead ground wire.

Since the more wires we use the better the protection, we can install additional wires on exposed places. The guard wire should be grounded at every pole if possible, but under no circumstances should the distance between successive grounds be more than five hundred feet.[†]

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[*] Committee on "Lightning Protection" N.E.L.A. May 1908.

[†] Still: Electric Power Transmission, 1919.

THE GAP TYPE OF LIGHTNING ARRESTER.

With this type of arrester, as soon as the voltage rises beyond the value for which the spark gap is set and discharges, the system is short-circuited to ground, until the arc rises and gradually blows itself out. As this requires an appreciable time, motors and converters have usually dropped out of step, and the generators have broken synchronism, that is, the system is shut down and has to be started up again. This type of protection therefore is not particularly favored in systems which require reasonable continuity of service, but if used, it is considered rather as an emergency device.

However, the spark gap type of arrester, is of immeasurable value when used with other arresters, namely electrolytic, oxide film, etc. These arresters would be valueless were it not for the spark gap arresters. Therefore, while this type of arrester is in itself an inadequate protection device for high tension lines, it is highly essential when used as a "blow-off valve" in series with other arresters.

SPHERE GAPS.

Introduction.

In general, a high-tension lightning arrester consists of two distinct parts: First, a spark gap for discharging abnormal voltages; second a means for preventing the normal voltage of the line from discharging. The problem of line-voltage protection has been given quite a bit of consideration, and it is only within recent years that engineers have considered the gap part of the arrester.

One of the requirements of an ideal arrester is that it shall not discriminate in its protective power, as regards wave shape or frequency, for any specified voltage. It is quite a simple matter to design a gap for abnormal voltage of low frequency, but when we have to deal with steep wave fronts, called impulse voltages, there are certain complications that arise due to dielectric spark lag.

Many peculiar failures of insulation, line insulators, etc., occur, due to lightning or surges. Lightning may pass a needle gap set at

a low voltage and strike across a higher voltage gap at the busbars or over a line insulator, etc. It requires small but finite time for a spark to form, depending upon the spacing, shape of conductors, etc.; most of such phenomena are caused by voltages of steep wave front or of extremely short durations, where the time to form a spark is limited.

OBSERVATIONS.

The time required to spark over agap varies with the spacing and shape of the electrodes. For a given 60 cycle voltage setting the time required to form a spark is greatest for gaps between points and least for gaps between well rounded surfaces. For spheres the time lag is so small that discharge takes place before the impulse voltage can rise appreciably above the continuously applied or 60 cycle spark over-voltage.

Suppose we place a sphere gap and a needle gap in multiple and apply both steep and slanting waves across these gaps to break them down. When the steep wave is applied to this combination the sphere will always spark out. When the slanting wave is applied the needles will spark over before the voltage point of the sphere gap setting. Thus a spark may be made to strike over each gap at will by a change in wave shape the steep waves passing between the sphere and the

slanting waves between the needles. Spheres are always very much "faster" than needles.

The reason for the difference in time for spark over needles and spheres seems clear. The spacings for a needle gap and a sphere gap set at the same 60 cycle or continuously applied break-down voltage are not the same. The needle spacing is much greater than the sphere spacing. Before the needle gap can spark over, brushes or "spheres" of corona must first form about the points and finally spark over takes place from the two "corona electrode" surfaces. The energy must be supplied thruthis air as it is ionized. The capacity between the points changes as the corona forms. This capacity must be gradually charged thru the corona resistance before different sections are brought up to the break-down voltage gradient. A vast amount of air must be torn apart or brought to ionic saturation. This may be readily observed by gradually apply-ing voltage to the needles in the dark. The sphere

spark-over requires breakdown of only a very small short tube, along the shortest distance between the spheres. The stress is practically uniform over this tube and breakdown takes place all along this tube at practically the same time.

APPLICATION.

The result of these facts developed by experiment is that the sphere gap is universally addpted as best fitting the requirements of a lightning arrester. It has been shown that the sphere is the "fastest" type of gap. But another phase of the arrester must be considered. That is, once the arc is formed the normal line voltage also discharges through the low-resistance path thus formed, and consequently we have the line short-circuited to ground.

To overcome this the horn-gap has been devised. It is so called because of the peculiar shape of the electrodes. They consist of two wires, bent, in the shape of "goat-horns", away from each other as shown in fig. 8 6. The discharge occurs across the narrowest part of the gap and an arc is formed. The path of the current thru the lower portion of the horn-shaped wires and the bridging arc is in the shape of an inverted U, and the magnetic field

on the inside of this curve forces the arc upward, thereby increasing its lenght until the arc breaks. The heat produced also has some effect in blowing the arc upward.

The latest development of spark gap arrester is the form shown in fig. 8G. It consists of a complex arrangement of sphere and horn gaps in multiple. The first discharge occurs across the lower gaps, from which if the arc persists, it rises to the upper set of spheres, to the horn gap and is extinguished.

IMPULSE GAPS.

Introduction.

A great advance has resulted in the use of spherical electrodes in combination with the horn gap arrester, in the problem of securing adequate protection against steep wave front line disturbances. By the use of this type of gap the operating engineer may be sure that the voltage to ground at thepoint at which the arrester is installed will never appreciably exceed the 60 cycle discharge voltage of the gap. But in this connection it must be mentioned that the danger to apparatus from an impulse voltage may be all out of proportion to the actual magnitude of the impulse. Take for example a transformer winding designed for 50,000 volts. If 100,000 volts at normal frequency be applied to the transformer winding, the stresses on the insulation will only be doubled. But if a high-frequency impulse of 100,000 volts be applied the stresses on certain parts of the insulation may be many times normal because of the "piling up" effect of the steep wave

front on the end turns of the winding, Consequently if we are to protect against such disturbances the gap used should be selective in its action; that is, it should discharge a high frequency impulse at a lower voltage than an abnormal voltage at normal line frequency.

The need for the selective action referred to above is emphasized by the consideration of the possible combinations of a high frequency impulse with the normal line-voltage wave. We will consider the three combinations shown in fig. 1C, and their effect on a winding protected by an ordinary gap.

Case A.- When an Impulse Occurs at the Zero Point of Line E. M. F. Wave.

In this case the presences of line voltage does not affect the action of the impulse. The insulation stresses in a winding and the discharge characteristics of a gap protecting a winding will be the same as if the impulse alon wer applied.

Case B. - Impulse Occurring at the Peak

of the Line E. M. F. Wave and Adding Thereto.

In this case the total emf. impressed on the gap and tending to discharge it is equal to the sum of the line voltage and the impulse voltage. The insulation stresses between the turns of the winding, on the other hand, are largely dependent on the value of the impulse alone, since line frequency does not cause a high voltage between turns. It would appear that in this case the gap affords a better protection than in Case A. For example assume the gap to be set at double line voltage. In case A, an impulse of twice the line voltage must be impressed before the gap will function while in case B, the maximum impulse that can be applied to the winding without causing the gap to discharge is just equal to the line voltage.

Case C.- Impulse Occuring at the peak of the line E. M. F. Wave and subtracting Therefrom.

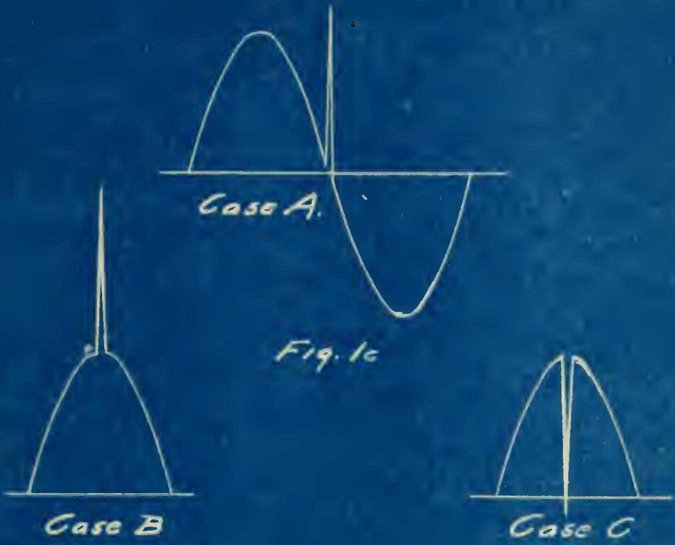
In this case it is obvious that the gap furnishes much less protection than in the preceding two cases. A very considerable impulse

voltage may be impressed on the winding without causing a rise in voltage across the gap. The presence of the line-frequency wave prevents the impulse from causing a rise in voltage across the gap but does not prevent the full destructive effect of the impulse from being felt on the winding. Assuming, as in the previous case, that the gap is set for double line voltage, it will be seen that an impulse of double line voltage may be applied without causing any rise whatever in the voltage across the gap, while it will require an impulse of three times line voltage to cause the gap to discharge.

Adequate protection against such a combination of high frequency with normal line frequency demands the use of a gap which is sensitive to steep wave fronts. While it is true that, if the impulse is oscillatory, the second half-cycle may cause an ordinary gap to discharge, such a discharge is too late to protect the winding against the destructive affects of the first half-cycle of the impulse.

PRINCIPLE.

Experimental investigation of impulse phenomenon has lead to the development of a new type of gap for lightning arrester service, which possess in amarked degree the selective properties referred to in the preceding introduction. The gap has been termed the "impulse protective gap" because of its particular effectiveness in discharging line disturbances of steep wave front. The general principle underlying the action of the gap is comparatively simple. In its most elementary form it consists of two gaps in series, each gap being shunted by a relatively high impedance. At line frequency these are proportional to the respective discharge voltages of the gaps which they shunt, but they are designed to change at different rates with changes of frequency so that, under the action of a high frequency impulse, one of them becomes much greater than the other and causes most of the high-frequency voltage to be impressed on one of the gaps. The breakdown of this gap will result in the total voltage being impressed on the remaining gap, which in turn will break down.



Case A.

Case B

Case C

Fig. 1c

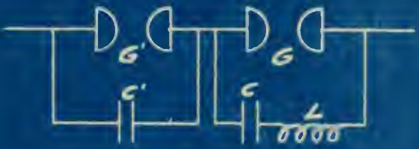
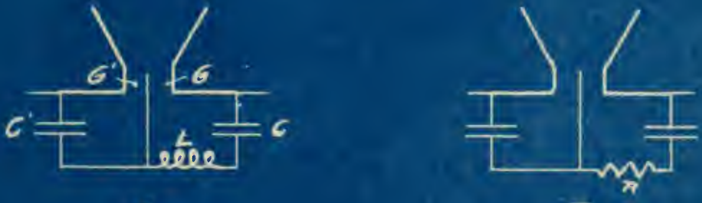


Fig. 2c



A

B

Fig. 3c

IMPULSE GAP TESTS.

In fig. 2c is shown a diagrammation representation of a gap constructed according to the above principle. One of the two equal gaps G and G' is shunted by a condenser C' and the other by an equal condenser C and an inductance L. At line frequency the inductive reactance of L is inappreciable compared with the condensive reactances, and therefore causes no unbalance in the voltage across the two gaps. To a high-frequency impulse, however, the condensers offer very little impedance and most of the inductance L, and thus across the gap G. Discharge of the gap G is, in general, immediately followed by a discharge across G'.

It has been found by experiment that better results are obtained by using a single gap, having an intermediate electrode, rather than two distinct gaps. Fig. 3c shows two types of gaps constructed in this manner. Circuit A shows a horn gap having an auxiliary electrode mounted between the horns: The auxiliary electrode connect-

ed to one of the horns thru a condenser C' and to the other thru a condenser C and an inductance L. The action is similar to that of the first circuit described.

In place of the reactance L, (~~a resistance may be imployed~~) a resistance may be used, as shown in circuit B. This is the preferred form of gap from a commercial standpoint, since the inductance used in A must necessarily be quite bulky, unless condensers of unreasonably high capacity be used. With the form shown in B, it has been found possible to secure excellent results with capacities as low as 10^{-11} farads.

Further tests were conducted on different types of gaps, as to shape of electrodes, various combinations of reactances etc., and the results indicated that the scheme B shown in fig. 3C was the most promising, for commercial development. A wire of small diameter (practically a pointed electrode) was found to be most satisfactorily for the auxiliary electrode. The pointed auxiliary

electrode gave results so much superior to a spherical or cylindrical electrode that further experiment with these latter forms was dropped.

As a result of these preliminary experiments it was decided to make complete tests on the two forms shown in the illustrations figs. 4c and 5c. These two gaps differed only in the shape of the horn electrodes. The gap in fig. 4c had plain horn electrodes made of 3/8 in. diam. brass rod, while the other gap had brass hemispheres 2.5 in. in diameter clamped to the horns. In both gaps the auxiliary electrode consisted of a blunt point of copper wire 0.025 in. in diameter. During the tests, each horn was supported on a pillar insulator composed of three porcelain pillar units. The units composing the pillars were of special design, having an unusually high electrostatic capacity, approximately 2×10^{-10} farads. Two of these units in series were used as the condensers between the auxiliary electrode and each of the horns (corresponding to C and C'

in circuit B fig. 3c). A water tube was used for the resistance, approximately 100,000 ohms. The wave adopted as a standard for these tests was a critically damped impulse having a wave front corresponding to a 500,000 cycle sine wave.

RESULTS OF IMPULSE TESTS.

The first series of experiments made was for the purpose of determining the effect of the presence of the auxiliary electrode on the 60 cycle discharge voltage of the two forms of gaps tested. Careful tests were made at gap settings ranging from ½ in. to 3 in. The results of these tests indicated that the presence of the auxiliary electrode does not appreciably lower the 60 cycle discharge voltage. With the auxiliary electrode in place, breaks were somewhat less consistent than with the plain gap, but the irregularities were not of sufficient magnitude to indicate an appreciable lowering of the breakdown voltage.

The two forms of impulse gaps shown in Figs. 4&5C were then tested for both the 60 cycle breakdown and the 500,000 cycle impulse breakdown with various gap-settings ranging from ½ in. to 3 in. The results of these tests are shown in the curves in figures 6, 7, 8 and 9C. Figs. 6 & 7C give the 60 cycle and impulse discharge voltages

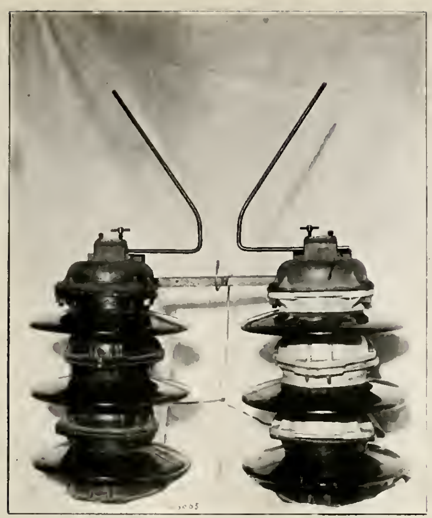


Fig. 4C.

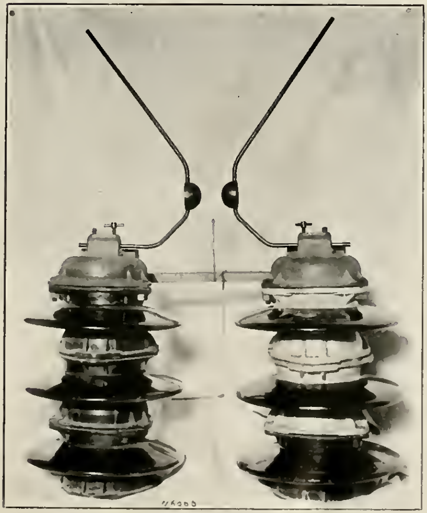


Fig. 5C

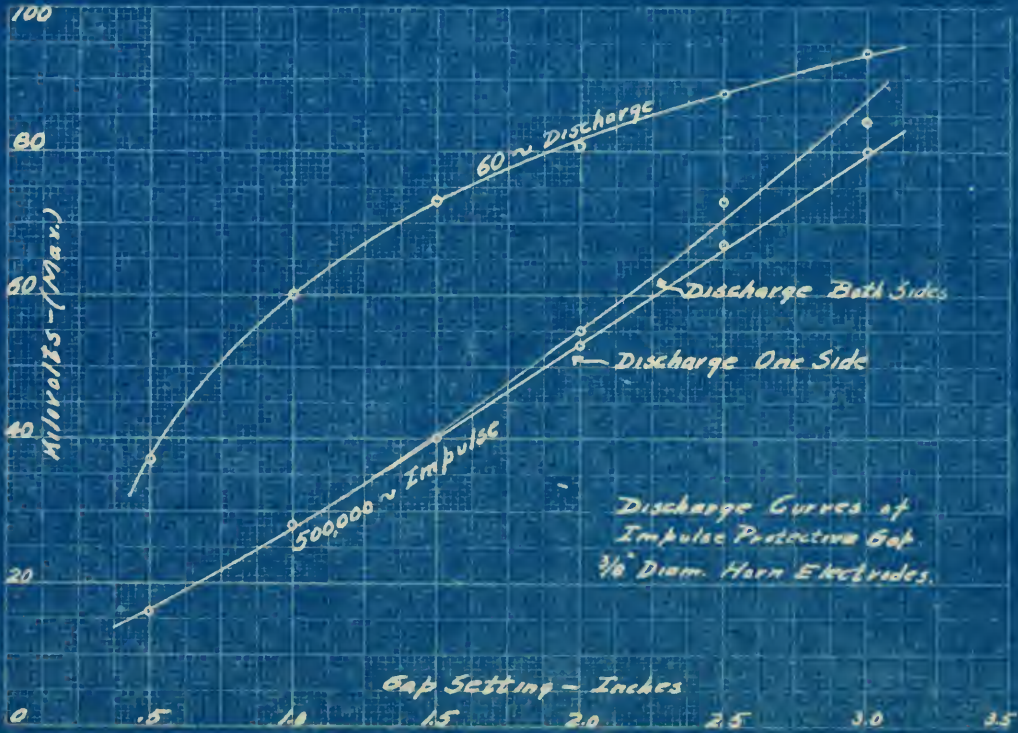

Kilovolts – (Max.)
100
80
60
40
20
0
.5
1.0
1.5
2.0
2.5
3.0
3.5
Gap Setting – Inches
60 ~ Discharge
500,000 ~ Impulse
Discharge Both Sides
Discharge One Side
Discharge Curves of
Impulse Protective Gap
3/8" Diam. Horn Electrodes.

Fig. 6a.

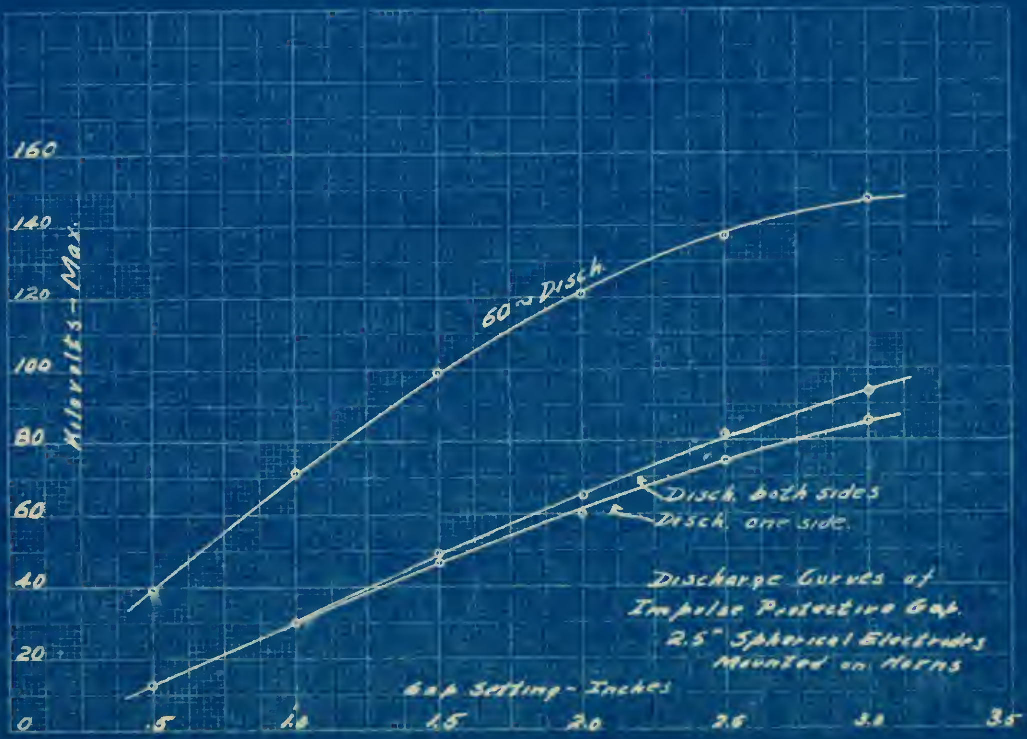

160
140
120
100
80
60
40
20
0
Kilovolts - Max.
60 ~ Disch.
Disch. both sides
Disch. one side.
Discharge Curves of
Impulse Protective Gap.
2.5" Spherical Electrodes
Mounted on Horns
Gap Setting - Inches
.5
1.0
1.5
2.0
2.5
3.0
3.5

Fig. 7c

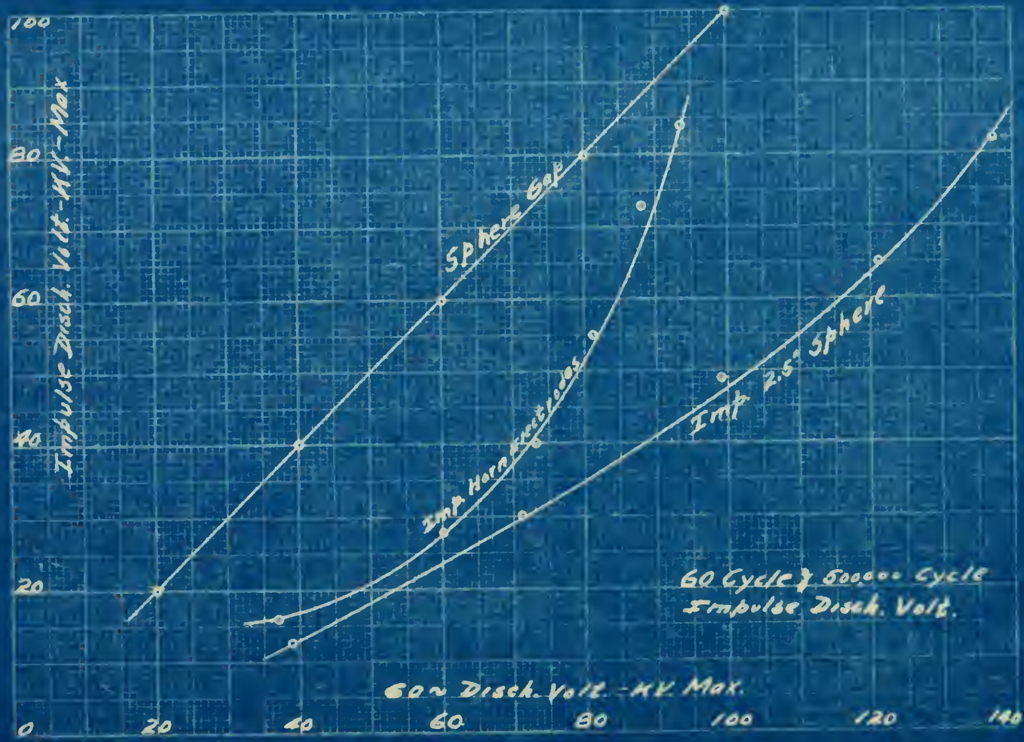

Impulse Disch. Volt.-KV.-Max
100
80
60
40
20
0
20
40
60
80
100
120
140
60~ Disch. Volt.-KV. Max.
Sphere Gap
Imp. Horn Electrodes
Imp. 2.5" Sphere
60 Cycle & 500000 Cycle
Impulse Disch. Volt.

Fig. 8c.

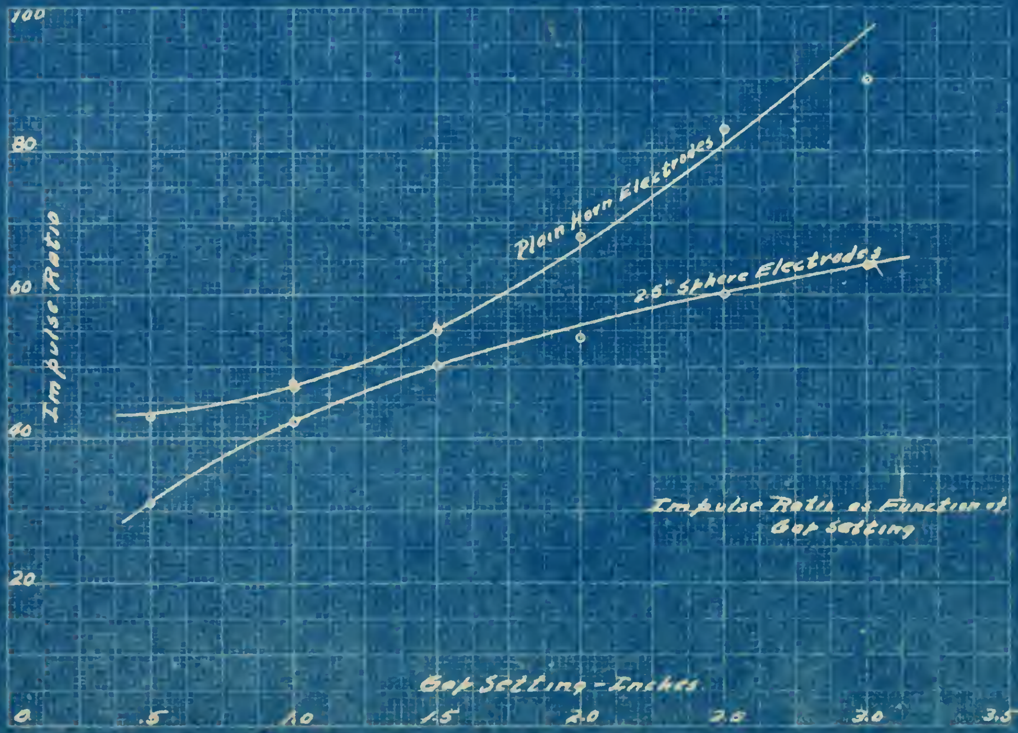

Impulse Ratio
100
80
60
40
20
0
.5
1.0
1.5
2.0
2.5
3.0
3.5
Gap Setting - Inches
Plain Horn Electrodes
2.5" Sphere Electrodes
Impulse Ratio as Function of
Gap Setting

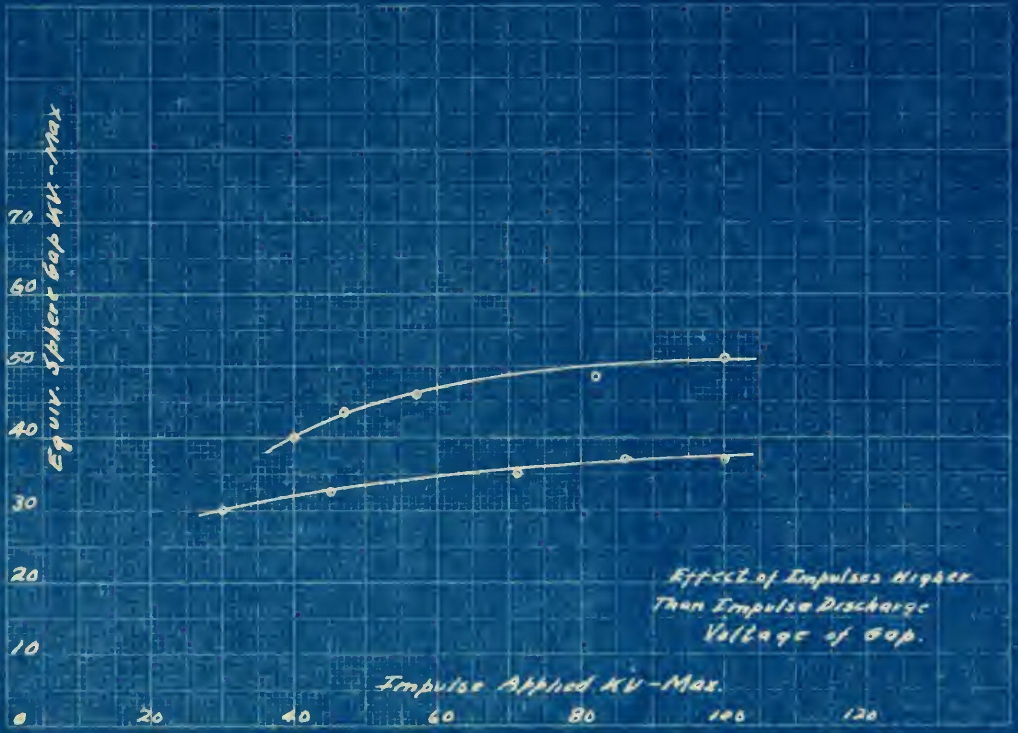
Fig. 9c.

as a function of gap setting for the two forms of gap shown in fig. 4+5C respectively. It will be seen that in every case the impulse discharge voltage is less than the 60 cycle breakdown, indicating an impulse ratio of less than unity.

(The "impulse ratio" is defined as the ratio of the impulse breakdown voltage of a gap to the continuously applied breakdown voltage.) In fig. 8C the impulse discharge voltages are plotted against the 60 cycle discharge, for the two forms of impulse gap and for the plain sphere gap. Fig. 9C shows the impulse ratio of the two gaps as a function of gap setting. It will be noted that with the form of gap having plain horn electrodes, the impulse ratio increases rapidly with the large gap settings and will probably become higher than unity for gap settings much in excess of 3 in. Where spherical electrodes are used it is evident from the curves that the impulse ratio will remain well under unity even for gap settings considerably greater than 3 in. The reason for the

superiority of the gap equipped with spherical electrodes may be made clearer by reference to Fig. 6 & 7c. By comparison of these curves it appears that, for a given gap setting, the impulse discharge voltages of the two gaps do not differ greatly. That is to say, a very great change in the shape of the main electrodes does not affect the impulse discharge voltage to a corresponding degree. We know, however, that the shape of the main electrodes will very materially modify the 60 cycle discharge. In view of these facts it is obvious that the lowest impulse ratio will be obtained by so shaping the main electrodes as to give the highest possible 60 cycle breakdown voltage. This condition is approximated with spherical electrodes.

A consideration of the foregoing results seems to lead to the conclusion that the impulse gap has great possibilities as a protective device. However, these results are by no means conclusive. The action of the gap under more adverse conditions


Equiv. Sphere Gap KV-Max
70
60
50
40
30
20
10
0
20
40
60
80
100
120
Impulse Applied KV-Max.
Effect of Impulses Higher
Than Impulse Discharge
Voltage of Gap.

Figs. 10 & 11c.

must be studied before its protective value can be regarded as definitely established. While it has already been shown that the impulse gap will discharge a much lower impulse voltage than a sphere gap having the same 60 cycle discharge, there remains the possibility that the gap may exhibit large time log when an impulse considerably in excessof its discharge voltage is applied, thus permitting the voltage to rise to a dangerous value before discharge takes place. This condition was tested by determining the "equivalent sphere gap" of an impulse gap subjected to a transient voltage.

The results of two series of tests made are given in the curves in figs. 10 and 11c. In obtaining these results a sphere gap was connected in parallel with the impulse gap under test. Then a setting of the sphere gap was found that would permit the two gaps to share the discharge equally when a given impulse voltage was applied.

If we assume the time lag of the sphere gap to be negligible, this "equivalent sphere gap" setting is a measure of the actual voltage to

which the impulse gap permits an impulse of super-discharge to rise. Figs. 10 and 11c show that the two forms of impulse gap do permit of some rise in voltage above the minimum impulse discharge value, but this rise is not of sufficient magnitude to cut down seriously the degree of protection afforded. Even with an impulse applied, having a value of three times the minimum discharge voltage, break-down occurs at very much lessthan the 60 cycle discharge voltage.

In addition to the above tests, it was thought desirable to undertake further experiments to determine the discharge characteristics of the impulse gap with frequencies other than 500,000 cycles. Fig 15 shows the results of these tests. It will be seen that the impulse discharge voltage increases slightly with increasing steepness of wave font applied. This increase in discharge voltage with increasing frequency is not very good so it was not deemed necessary to make a complete series of tests at other than 500,000 cycles.

It is a reasonable assumption that the tests made at this latter frequency will represent a fair average value of the discharge characteristics of the gap under the action of high-frequency transients liable to occur in practise.

RESULTS OF TESTS.

Impulse Voltages Superimposed on 60 Cycle Wave.

In making tests with an impulse voltage superimposed on a 60 cycle wave the 60 cycle voltage applied was equal to one-half the discharge voltage of the gap. With this 60 cycle voltage applied the value of the impulse voltage required to cause discharge was determined both for an impulse adding to the 60 cycle wave and for an impulse subtracting therefrom. This test may be regarded as one closely related to conditions that may occur in practise. Having the gap set for a discharge voltage equal to twice the 60 cycle voltage applied, was taken as a fair approximation of the usual practise with regard to the setting of lightning arrester gap

The results of the tests made are given in tables 1 and 2 of fig. 13c . In column 3 are given the real peak values of the 60 cycle voltages applied at the different gap settings. This is equivalent to the peak value of voltage from one line to ground which is applied to a lightning

Impulse Protective Gap Tests with 500,000

Impulse Superimposed on 60 Cycle Wave

Gap setting. Inches	60-cycle discharge. kv. max.	60-cycle voltage applied. kv. max.	Impulse required to cause discharge		Equivalent line voltage kv. r. m. s.
			Case B kv. max.	Case C kv. max.	
Table 5:--¾ in. diam. Horn Electrodes					
1.0	60	30	9	30	36.5
1.5	73	36.5	16	45	44.5
2.0	81	40.5	20	52	49.5
2.5	88	44	40	71	54
3.0	93.5	47	41	90	57
Table 6:-- 2.5 in. Spherical Electrodes					
1.0	71	36	9	32	44
1.5	99	49.5	18	47	60.5
2.0	121	60	22	68	73.5
2.5	137	68	32	84	83
3.0	147	73	45	96	89

Figure 13 C

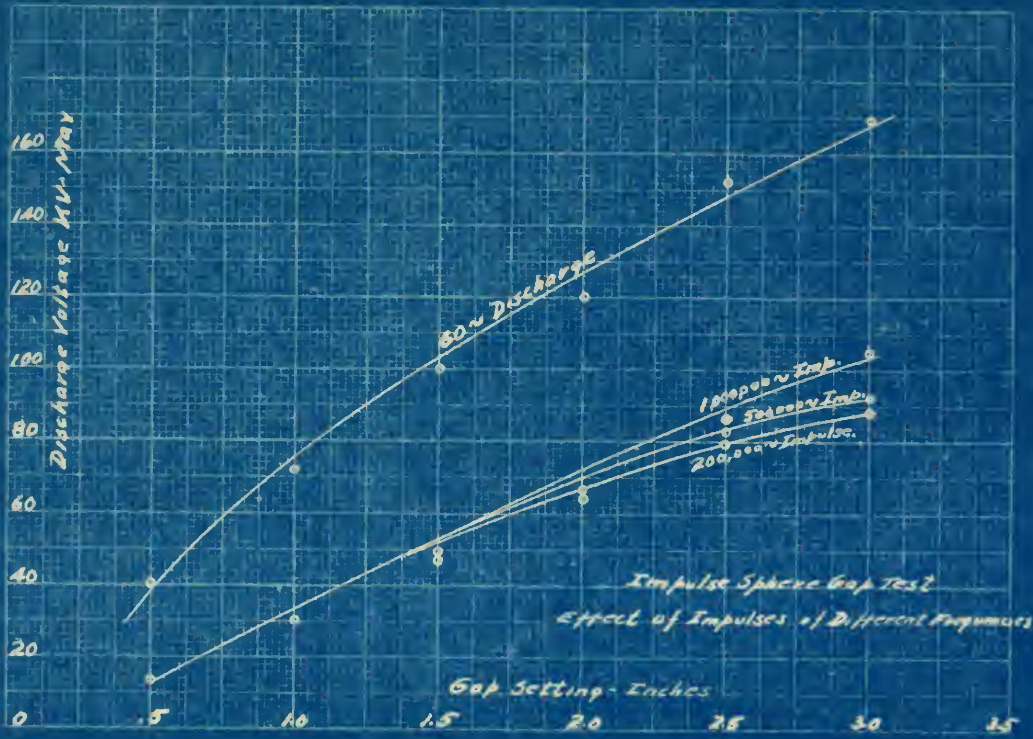

Discharge Voltage KV-Max
0
20
40
60
80
100
120
140
160
.5
1.0
1.5
2.0
2.5
3.0
3.5
Gap Setting - Inches
60 ~ Discharge
1,000,000 ~ Imp.
500,000 ~ Imp.
200,000 ~ Impulse.
Impulse Sphere Gap Test
Effect of Impulses of Different Frequencies

Fig 12c

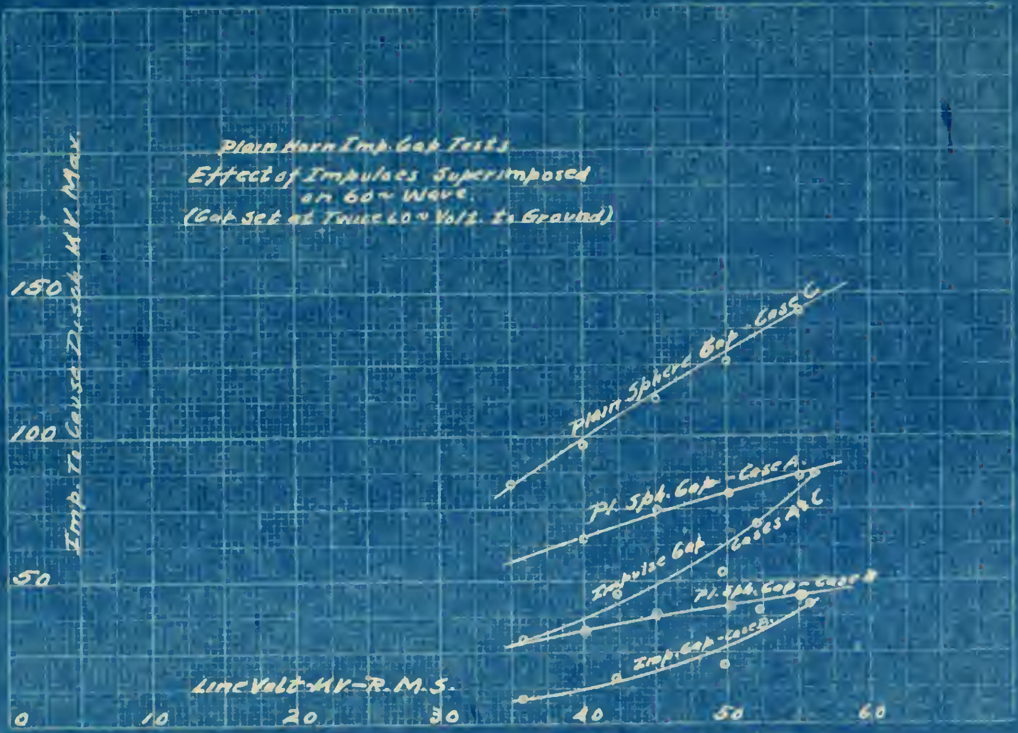

Plain Horn Imp. Gap Tests
Effect of Impulses Superimposed
on 60~ Wave.
(Gap set at Twice 60~ Volt. to Ground)
Imp. To Cause Disch. K.V. Max.
150
100
50
0
10
20
30
40
50
60
Line Volt-K.V.-R.M.S.
Plain Sphere Gap - Case C
Pl. Sph. Gap - Case A
Impulse Gap - Cases A & C
Pl. Sph. Gap - Case B
Imp. Gap - Case B

Fig. 14c.

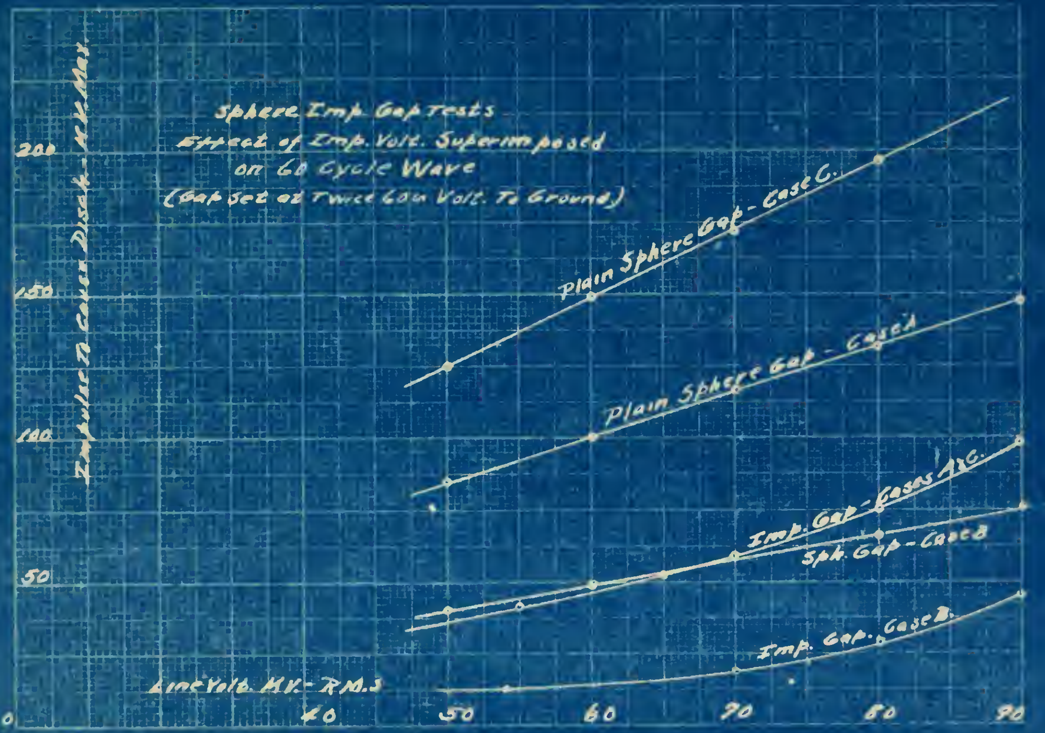

Sphere Imp. Gap Tests
Effect of Imp. Volt. Superimposed
on 60 Cycle Wave
(Gap Set at Twice 60∼ Volt. To Ground)
Impulse to cause Disch.-K.V. Max.
200
150
100
50
0
Line Volt. K.V.-R.M.S
40
50
60
70
80
90
Plain Sphere Gap - Case C.
Plain Sphere Gap - Case A
Imp. Gap - Cases A & C.
Sph. Gap - Case B
Imp. Gap. Case B.

Fig. 15C.

arrester gap in service . To form a more convenient basis for service conditions, the root-mean-square value of the three-phase line voltage, equivalent to this peak voltage to ground, is given in the last column. Figs. 14 and 15c shown graphically the impulse voltage required to cause discharge as a function of this equivalent line voltage. The curves for case A are taken from the results given in fig. 6, 7, 8 and 9c, for the impulse voltage alone. For both forms of gap, the results for cases A and B are practically identical. In addition to the curves for the impulse gaps, the characteristics of a plain sphere gap are shown for the purpose of comparison. The curves for the sphere gap are computed assuming an impulse ratio of one. The computed values check with actual tests.

Fig. 14 and 15c are particularly effective in showing the very superior protection afforded by the impulse protective gap when subjected to an impulse subtracting from the 60 cycle wave (Case C). For example, on a 66,000

volt line an impulse protective gap would discharge such an impulse having a value of but 56 kv. max. (see fig. 14c) while a plain sphere gap would require an impulse of 161 kv. max. to cause a discharge under the same conditions.

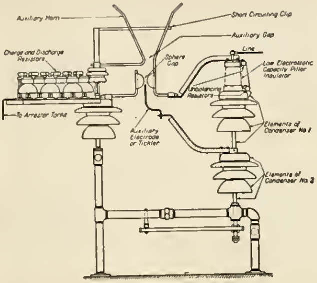

Auxiliary Horn
Short Circuiting Clip
Auxiliary Gap
Line
Charge and Discharge Resistors
Sphere Gap
Low Electrostatic Capacity Pillar Insulator
Unbalancing Resistors
To Arrester Tanks
Auxiliary Electrode or Tickler
Elements of Condenser No. 1
Elements of Condenser No. 2

Fig. 16c.

CONCLUSION.

To secure adequate protection against line disturbances of steep wave fronts it is important that a gap having the lowest possible impulse ratio be used. A gap with an impulse ratio of less than unity is particularly desirable.

There are certain combinations of high-frequency impulses with line-frequency waves for which the degree of protection offered by the ordinary sphere gap is lessened. The need for a protective gap having selective properties making it sensitive to steep wave fronts is thereby emphasized. A protective gap having such properties may be constructed without greatly complicating the usual horn and sphere-gap structure. Exhaustive tests have shown it to be superior to the ordinary sphere-horn gap, even under the most unfavorable.

It is probable that the usual type of protective gap will be replaced by the newer type of impulse gap described. Manufacturers of apparatus have realized the advantages of the device and have placed it on the market. One type of commercial gap is shown in fig. 16C.

CHOKE COILS.

In the previous chapter we have been discussing the effect of a change in the line constants on a travelling wave. We have seen that when a surge encounters a reactance there is a partial reflection of the wave, only a part being transmitted. We have also explained this in another way. When travelling wave encounters a reactance, the voltage at that point rises above the surge potential, since a reflection takes place like on the open end of a transmission line. A reactance is similar to an open end in as much as it takes time to establish a current through an inductive circuit. So we can see that at the moment a surge arrives at the point of an appreciable inductance, the inductance has nearly the same effect on the surge as an open circuit would have. There is also a change in frequency at the transition point. In general, the transmitted waves will have a lower frequency and a smoother wave front than the original waves.

This affect is taken advantage of in the use of reactive coils in the transmission lines in or near the stations, or where protection against surges is desired. The coil lowers the frequency of the wave front, so that whatever charge gets through the choke coil will be of a frequency too low to cause a serious drop of potential around the first turns of the end coils in any reactive apparatus.

In connection with the study of sphere gaps and horn gaps it was noted that any gap has a certain dielectric lag, that is, it does not discharge instantly when a high potential is applied but that it takes some time, usually very short, after the application of the breakdown potential, before the gap discharges. Now since a choke coil, due to its inductive effect, can not pass a travelling wave instantly, we can look upon its action as "holding back" the disturbance until the lightning arrester has time to discharge it to earth. From the above we see that choke coils by themselves can not be considered as giving complete protection against lightning disturbances,

but are to be considered as auxiliaries to lightning arresters.

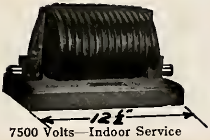
In America, the general practice is to use choke coils on lines where the voltage is at least 5000 volts. Lines and apparatus operating at a lower potential than 5000 volts have generally a quite liberal factor of safety in the insualtion, hence there is less necessity for using choke coils. Hence we confine the use of choke coils to lines operating at voltages higher than 5000 volts, and to lower voltage lines only when the installation calls for the best protection available, regardless of the extra cost. Choke coils should be used when arresters are connected directly to overhead lines. When arresters are connected to bus bars the choke coil should not be placed between the line and the bus, but between the bus and the reactive apparatus, whether it be a generator or a trasformer. In general, the relative position of the choke coil and the lightning arrester should in all cases be such that

the surge first meets the arrester, and then the choke coil. The reactive apparatus, such as transformers or generators is to be placed beyond the choke coil. Choke coils should not be used in connection with circuits of considerable capacity such as underground cables, as dangerous "resonance" voltages may be set up even by comparatively small disturbances. In any case the use of the choke coils on such circuits should be preceded by a very careful consideration.

A pertinent question is what should be the value of the inductance of a choke coil. If the inductance is too high, the surges originating in the generators or the transformers are likely to be prevented from passing out on the line. A high inductance will have an appreciable reactive drop which will be objectionable so far as the regulation of the system is concerned. It may also set up high resonant voltages if continual surges occur in the circuit. A very low inductance, say a few turns, again would not give any appreciable degree of protection.

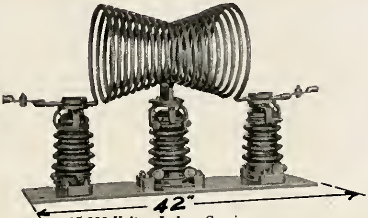
For the above reason, then, a medium inductance is usually employed. The inductance is usually in the order of a fraction about one-tenth of a millihenry. One half of a millihenry would be about the upper limit, while about five-hundredths of a millihenry, would be the lower limit.

The choke coils for indoor use on circuits not exceeding 7500 volts and 200 amperes, consist of a cylindrical coil of insulated copper wire rigidly mounted as illustrated in fig. 1. The coils for higher voltages are usually made of the hour-glass type or of the suspension type. Both of those types are generally made of bare copper wire or rods. The General Electric Company uses copper in the manufacture of all of their standard types. Copper has the advantage over other metals of having low specific resistance and comparatively high mechanical strenght. It permits the making of a coil of the smallest dimension for a given current-carrying capacity. The strength of the copper in the hour glass makes unnecessary



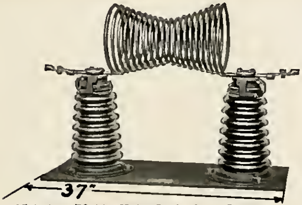
7500 Volts—Indoor Service

Fig. 1 D.



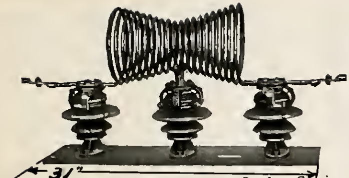
15,000 Volts—Indoor Service

Fig. 2 D



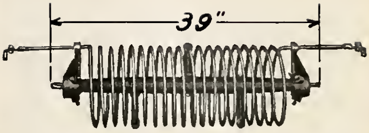
25,000 to 73,000 Volts Inclusive—Indoor Service

Fig. 3D



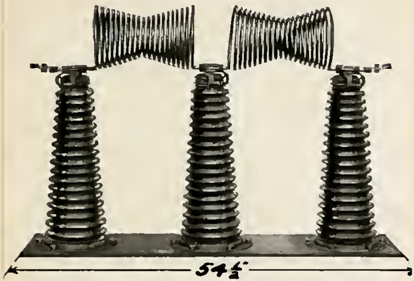
15,000 to 25,000 Volts Inclusive—Outdoor Service

Fig. 4D.



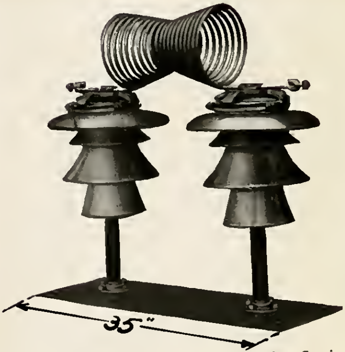
SUSPENSION CHOKE COIL

Fig. 5D



95,000 to 115,000 Volts Inclusive—Indoor Service

Fig. 6D



37,000 to 73,000 Volts Inclusive—Outdoor Service

Fig. 7D.

hour glass type. The strain insulator is amply strong to take up the transmission line pull, there being no pull on the coil itself. The suspension type should find a wider use than it has at present, since it can be mounted in any position and does not require any support or insulators for mounting.

THE MULTIGAP ARRESTER

Principle

A type of arrester which was almost universally in service before the advent of the aluminum cell and oxide film arrester is the multigap lightning arrester. As is well known, the essential elements of this arrester consist of a number of cylinders between line and ground, these cylinders being spaced with a small air-gap between them.

The multigap arrester is distinguished from the single gap arrester in that it can be made to discharge abnormal rises of potential without disturbing operating conditions. Under most conditions of operation, it discharges at a much lower voltage than does a single gap, the length of which is equal to the sum of the small gaps, and the interrupting power is such that the disturbing charge passes off without allowing the dynamic currents to follow for more than one-half cycle.

The cylinders of the multigap arrester

act like plates of condensers in series. (Fig. 1F). This condenser function is the essential feature of the operation. When a static stress is applied to a series of cylinders between line and ground, the stress is instantly carried from end to end. If the top cylinder is positive it will attract a negative charge on the face of the adjacent cylinder and repel an equal positive charge to the opposite face, and so on down the entire row. The second cylinder has a definite capacity relative to the third cylinder and also to the ground; consequently the charge induced on the third cylinder will be less than on the second cylinder, due to the fact that only part of the positive charge on the second cylinder induces negative electricity on the third, while the rest of the charge induces negative electricity to the ground. Each successive cylinder, counting from the top of the arrester, will have a slightly smaller charge of electricity than the preceding one. The condition has been expressed as "a steeper potential gradient near the line."

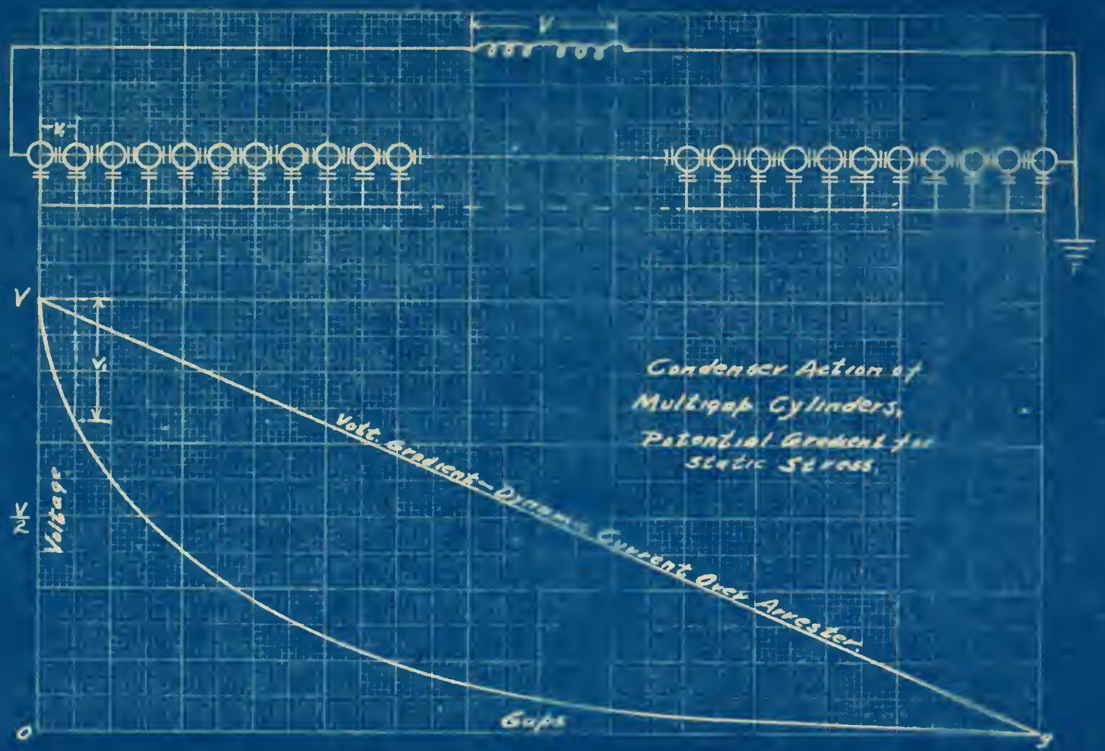

V
K
V
V
V_1
$\frac{V}{2}$
Voltage
0
Gaps
g
Volt. Gradient—Dynamic Current Over Arrester.
Condenser Action of
Multigap Cylinders,
Potential Gradient for
Static Stress.

Fig. 11

Sparking of the Gaps

The quantity of electricity induced on the second cylinder is greater than on any lower cylinder and its gap has a greater potential strain across it as shown in Fig. 1F. When the potential across the first gap is sufficient to spark, the second cylinder is charged to line potential and the second gap receives the static strain and breaks down. The successive action is similar to overturning a row of ninepins by pushing the first pin against the second. This phenomenon explains why a given length of air gap concentrated in one gap requires more potential to spark across it than the same total length made up of a row of multigaps. As the spark crosses each successive gap, the potential gradient along the remainder readjusts itself.

Generator Current Arc Extinguished

When the sparks extend across all the gaps the generator current will follow, if, at that instant, the generator potential is sufficient. On account of the relatively greater

generator current flow, the distribution of potential along the gaps becomes equal, and has the value necessary to maintain the generator current arc in the gaps. The generator current continues to flow until the potential of the generator passes through zero to the next half cycle, when the arc-extinguishing quality of the metal cylinders comes into action.

The alloy of which the cylinders are composed contains a zinc metal of low boiling point which prevents the reversal of the generator current. It is a rectifying effect, and before the potential again reverses, the arc vapor in the gaps has cooled to a non-conducting state, cutting off further flow of current. The action of the zinc vapor in cutting off the generator current which follows the lightning discharge is due to its rectifying qualities. In this respect zinc is, although to a less degree, like mercury. Some of the zinc is vaporized by the heat of the discharge and when the current in the gap passes through the zero point of the wave, the zinc vapor prevents its being re-established in the opposite direction. Thus, the generator current is always

cut off at the end of that half cycle in which the discharge takes place. This action is certain if the current is limited by resistances as described later.

Graded Shunt Resistance

The multigap arrester without the use of shunt resistance has the property of discharging more easily at high frequencies than at low frequencies. The demands on an arrester are that it should not discriminate with regard to frequencies for any set voltage.

Briefly stated, the problem to be worked out in the design of the graded shunt resistance type of multigap arrester is: to properly limit the dynamic current so that the arc may be extinguished; to arrange a shunt circuit so that the series resistance will be automatically cut out, if safety demands it, on account of heavy lightning stroke; and, while retaining these properties, to make the arrester sensitive to a wide range of frequencies. It should be noted that series resistance limits the rate of discharge of the lightning, as well as of the dynamic current.

The desired result is obtained by the use

of graded shunt resistance. Without regarding the "cumulative" or "breaking back" effect of the graded resistance, described later, this type of arrester may be considered as four arresters in one. First, for small discharges there are a few gaps in series with a high shunt resistance. This part of the arrester will safely discharge accumulated static, and also all disruptive discharges of small ampere capacity. (The following discussion refers to Fig. 2 without regard to the lower leg of gaps and resistances. That is, assume the three legs of gaps to be grounded just below GS, where they are tied together.) In Fig. 2 this path is shown through H (resistance) and GS (gaps). Second, there are a number of gaps in series with a medium shunt resistance which will discharge disruptive strokes of medium ampere capacity; in Fig. 2 this path is shown through M (resistance) and GH plus GS (gaps). Third, there is a greater number of gaps in series with a low shunt resistance which will discharge heavy disruptive strokes. In the figure this path is shown through L (resistance) and GM plus GS (gaps). Fourth and last, the total number of gaps has no series resistance, thus enabling the arrester to

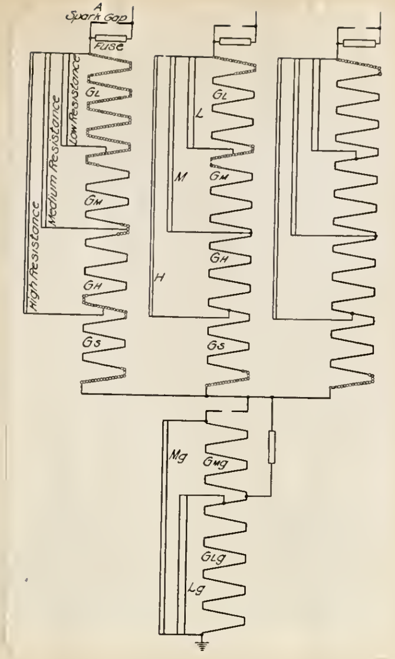

A
Spark Gap
Fuse
Low Resistance
Medium Resistance
High Resistance
GL
GM
GH
Gs
GL
L
M
GM
GH
H
Gs
Mg
Gmg
Glg
Lg

Fig. 2F

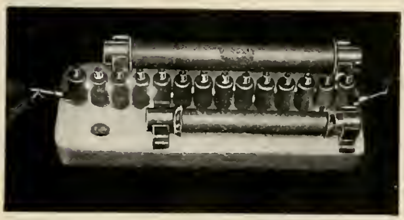


Fig. 5F

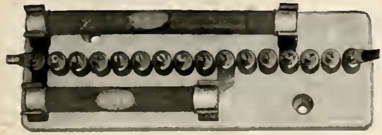


Fig. 4F

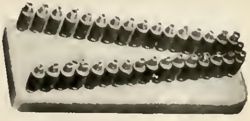


Fig. 3F

freely discharge the heaviest induced strokes. In Fig. 2F this path is shown through zero resistance and GL plus GM plus GH plus GS (gaps).

In each of the above circuits the number of gaps, and the resistance are so proportioned as to extinguish the dynamic arc at the end of the half cycle in which the lightning discharge takes place.

The "Cumulative" or "Breaking Back" Effect

The graded shunt resistances give a valuable effect not brought out in the previous description, where the arrester is considered as four separate arresters. This is the "cumulative" or "breaking back" action.

When a lightning strain between line and ground takes place, the potential is carried down the high resistance, H, to the series gaps, GS, and the series gaps spark over. Although it may require several thousand volts to spark across an air gap, it requires relatively only a few volts to maintain the arc which follows the spark. In consequence, when gaps GS spark over, the lower

end of the high resistance is reduced practically to ground potential. If the high resistance can carry the discharge current without giving an ahmic drop sufficient to break down the shunted gaps GH, nothing further occurs--the arc goes out. If, on the contrary, the lightning stroke is too heavy for this, the potential strain is thrown across the shunted gaps, GH, equal in number to the previous set. In other words, the same voltage breaks down both of the groups of gaps, GS and GH, in succession. The lightning discharge current is now limited only by the medium resistance, M, and the potential is concentrated across the gaps, GM. If the medium resistance cannot discharge the lightning, the gaps GM spark, and the discharge is limited only by the low resistance. The low resistance should take care of most cases, but with extraordinarily heavy strokes and high frequencies, the discharge can "break back" far enough to cut out all resistance. In the last step the resistance is relatively low in proportion to the number of shunt gaps, GL, and is designed to cut out the dynamic current instantly from the gap, GL, This "breaking

back" effect is valuable in discharging lightning of low frequency, in a manner better than has been obtained before.

After the spark passes, the dynamic arcs are extinguished in the reversed order. The low resistance, L, is proportioned so as to draw the dynamic arcs instantly from the gaps, GL. The dynamic current continues in the next group of gaps, GM, until the end of the half cycle of the generator wave. At this instant the medium resistance, M, aids the rectifying quality of the gaps, GM, by shunting out the low frequency dynamic current of the generator. On account of this shunting effect the current dies out sooner in the gaps, GM, than it otherwise would. In the same manner, but to a less degree, the high resistance, H, draws the dynamic current from the gaps, GH. This current now being limited by the high resistance, the arc is easily extinguished at the end of the first one-half cycle of the generator wave.

Arresters for Grounded Y and Non-Grounded Neutral Systems

The connection for a three-phase arrester, 33,000 volts between lines, are shown in Fig. 2F . The circuit as it is shown is used on delta, ungrounded Y, and Y systems grounded through a high resistance. For adoption on an ungrounded Y system the fourth arrester leg between the multiplex connection and ground is omitted, and the arrester is grounded where the three legs are tied together.

The difference in design lies in the use of a fourth arrester leg between the multiplex connection and ground, on ungrounded systems. The reason for introducing the fourth leg is evident. The arrester is designed to have two legs between line and line. If one line became accidentally grounded, the full line potential would be thrown across one leg, if the fourth or grounded leg were not present. On a Y system with a grounded neutral, the accidentally grounded phase causes a short circuit of the phase, and the arrester is relieved of the strain by the tripping of the circuit breaker.

Briefly stated, the **fourth or** ground leg of the arrester **is** used when, for any reason, the system could be operated, even for a short time, with one phase grounded.

Multiplex Connection

The multiplex connection consists of a common connection between the phase legs of the arrester better adapted to relieve high potential surges between lines than would otherwise be possible. Its use also economizes greatly in space and material for delta and partially grounded or non-grounded Y systems.

Ground Leg Partly Shunted by Fuse

This feature allows the breakdown point of the arrester to be more closely adjusted for the normal voltage of the system than would be possible without it, since, when normal conditions extist, only the Y voltage is impressed across the arrester from any phase to ground.

In the case of an accidental ground on one phase, however, the voltage between the other

two phases and ground is increased by the $\sqrt{3}$; thus requiring, in order to protect the circuits, the automatic introduction of additional gaps shunted by a fuse, which can be blown immediately by the current following the discharge.

Adjustable Gap in Each Leg Shunted by a Fuse

The adjustable gaps (see A, Fig. 24) are shunted by fuses as shown, which blow in case of continued abnormal high voltage thus saving the arrester and leaving the system protected. Further, in case of an arcing ground, such as is caused by a wire swinging against a tree, this spark gap makes the arrester less sensitive to the high frequency but still protects against lightning disturbances.

The resistances used in these arresters are permanent and are not affected by heating or by static discharges. They are glazed to prevent absorption and surface arcing. The contacts are made with metal terminals securely shrunk on the ends of the rods. This method prevents heating of the terminals, which might result from high con-

tact resistance, and greatly increases the capacity of the rod.

"Y" Unit for Multigap Arresters

The high-voltage multigap arrester is made up of "V" units as shown in Fig. 25, each consisting of gaps between knurled cylinders, and connected together at their ends by short metal strips. The base is of porcelain, which thoroughly insulates each cylinder, and insures the proper functioning of the multigaps.

Cylinders

The cylinders are made of an improved alloy that contain zinc metal of low boiling point which gives the rectifying effect, and metals of high boiling point which cannot vaporize in the presence of the one of low boiling point. The cylinders are heavily knurled. As the arc plays on the point of a knurl it gradually burns back and when the metal of low boiling temperature is used up, the gap is increased at that particular point. The knurling therefore, insures longer life to the cylinder, by forcing successive arcs to shift to a new point. When worn along the entire face, the

cylinder should be slightly turned.

Resistance Rods

The low resistance section of the graded shunt is composed of rods of a new metallic alloy. These rods have large current-carrying capacity, and practically zero temperature coefficient up to red heat.

The medium and high resistance rods are of the same standard composition previously used. The contracts are metal caps shrunk on the ends; the resistances are permanent in value and the inductance is reduced to a minimum. The rods are designed with a large factor of safety, and have sufficient heat absorbing capacity to take the dynamic energy following transitory lightning discharges. They are glazed to prevent absorption of moisture and surface arcing.

Types

Figure 3F shows the V unit form for use in arresters of the type shown in Fig. 2F. Fig. 4F shows a 2300 volt arrester for indoor service; the resistance of which there are two units for low

voltages, is shown mounted on either side of the cylinder gaps. Fig. 5F shown an arrester of this type in action, discharging and shunting the generator current.

THE ALUMINUM CELL LIGHTNING ARRESTER.

Introduction.

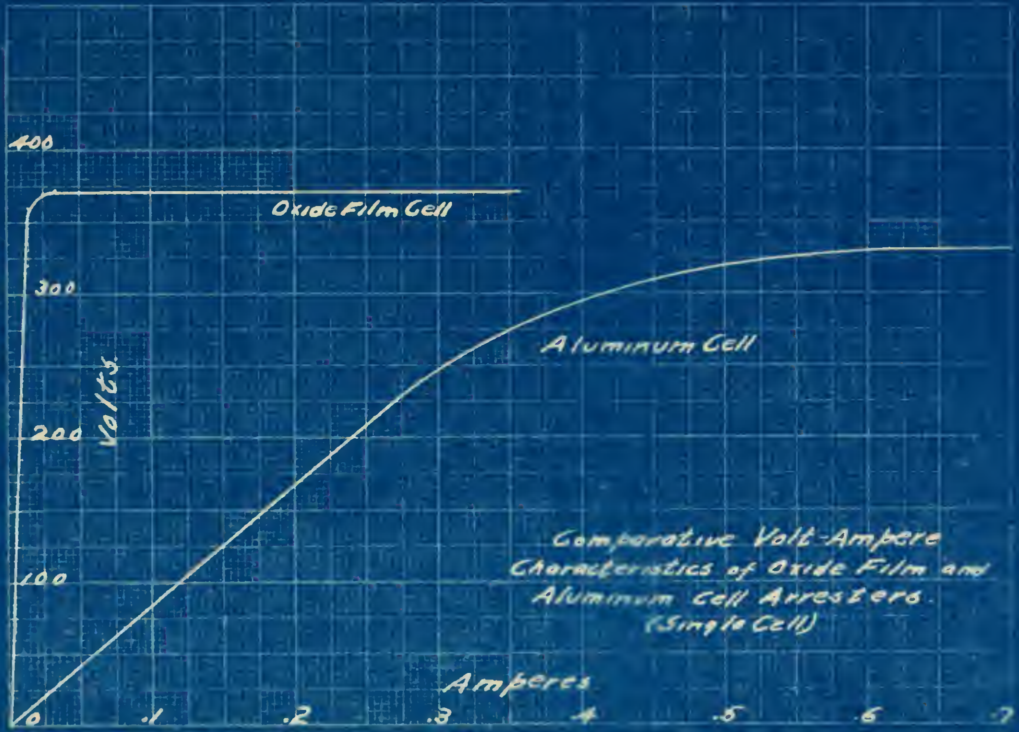
Recurrent surges on transmission lines must be handled by devices which do not short-circuit the system even for one-half wave, and which never allow the normal voltage of the system to pass a current over the arrester, but act as a short circuit for any excess voltage above the normal. This desirable condition is realized by the use of the aluminum cell arrester.

PRINCIPLE.

The design of the aluminum arrester is based on the characteristics of a cell consisting of two aluminum plates on which has been formed a film of hydroxide of aluminum immersed in a suitable electrolyte. This film is formed on the aluminum plates by a series of electro-chemical treatments. The action of the aluminum cell is as follows:

Up to a certain critical voltage the hydroxide film has the property of insulating, or

rather opposing the flow of current and is therefore closely analagous to a counter-emf. Up to this critical voltage only a small leakage and charging current can flow, but during any rise above this voltage the current flow thru the cell is limited only by the actual resistance of the electrolyte, which is very low. The action is comparable to that of the well known safety valve of a steam boiler by which the steam is confined until the pressure rises to a given value, at which point the valve opens and releases the excess pressure. It might also be compared to the action of a storage battery on direct current. Up to about two volts per cell, impressed, the storage battery, when charged, opposes an equal counter-emf., shutting of the flow of current; but, for voltage above this value the current is limited only by the internal resistance of the cell. This characteristic makes the aluminum cell ideal as a means of discharging abnormal potentials, or surges in electric circuits. It practically prevents the



Comparative Volt-Ampere
Characteristics of Oxide Film and
Aluminum Cell Arresters.
(Single Cell)

Fig. 16 (Aluminum)
Fig. 2H (Oxide)

flow of currents at operating voltages, but instantly short circuits such abnormal portions of a potential wave or surge as would be dangerous to the insulation of the system.

The thin surface layer of aluminum hydroxide, formed by currents passing thru the aluminum trays, has a very high resistance. For higher impressed voltages the hydroxide film becomes thicker and the resistance increases up to a critical voltage. For pressures above this critical voltage the hydroxide film breaks down and the high resistance is then removed from the circuit. While the range between partial and complete breakdown of the hydroxide layer is small the critical voltage is a fairly definite value as shown by the sharp bend in the curve in fig. 16. It is affected by the electrolyte used, the wave shape and other factors. If the current passess thru several trays in series the total resistance and likewise the total breakdown voltage is increased in proportion to the number of trays. Arresters designed for service

On high-voltage systems, therefore, have a sufficient number of trays arranged in series so that the voltage per tray is less than the critical voltage. For alternating currents it is customary to let the normal operating voltage be 300 volts or less per tray.

Besides the valve action described above there is another characteristic of the cell of great importance. The thin insulating film of aluminum hydroxide between the conducting aluminum and the conducting electrolyte acts as a dielectric and the cell therefore, is an electrostatic condenser. A condenser of this type makes an ideal path for high frequency lightning discharges. With these arresters, 1000 cycles, for instance, which is not an unusual frequency for lightning disturbances, would discharge almost 100 amperes without any rise in voltage.

Due to this capacity, the arrester cannot be connected permanently across an alternating voltage. The Charging current at normal frequency.

which is about .5 ampere, would in time heat the electrolyte. In every installation therefore, spark gaps set to are over at slight increase of voltage, insulate the arrester from the line.

Another characteristic of the aluminum cell is the dissolution of a part of the film when the plates stand in the electrolyte, and the cell is disconnected from the circuit. The film is presumably composed of two parts; one part is hard and insoluble, and apparently acts as a skeleton to hold the more soluble part. When a cell which has stood for some time disconnected, is reconnected to the circuit, there is a momentary rush of current which replaces part of the film which has been dissolved. All electrolytes dissolve the film, the extent ofthe dissolution depending upon the lenght of time the film is in the electrolyte, the electrolyte used and its temperature. This fact was perceived early in the preliminary investigations into the subject and it was realized that in order to use the general principle successfully in an arrester, it would be

necessary to provide means for easily and quickly reforming the film, or for what is called "charging". It is therefore necessary to charge the cells from time to time and thus prevent the dissolution and consequent rush of generator current which would otherwise occur. General Design.

In general the arrester consists of a stack of aluminum cells between lines and between lines and ground. The shape and arrangement of the aluminum trays, the space filled by the electrolyte, the oil insulation and terminal leads are shown in fig. 26. The shape of the tray is usually conical or a double cone for large sizes, but always so designed that gas bubbles formed during the discharge may escape. To provide a path of sufficiently low resistance so as to afford the required freedom of discharge when the high-voltage disturbance disrupts the hydroxide films, the cross-sectional active tray area is from 90 to 100 sq. in. The stack is built up of these aluminum cones supported on treated wooden rods and separated from each other by

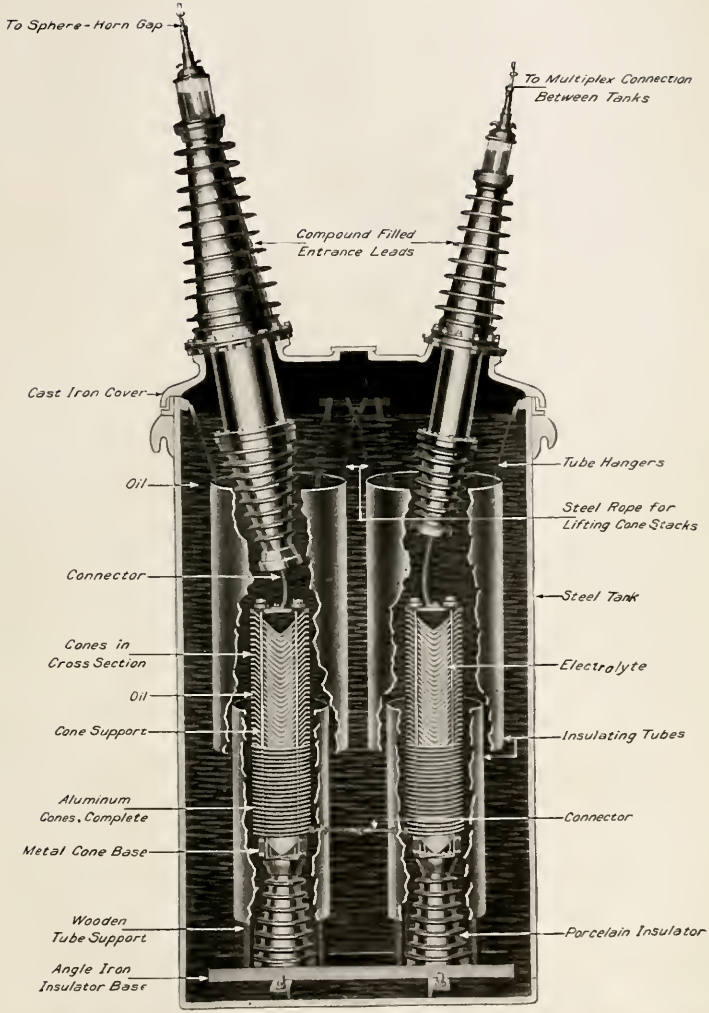

To Sphere-Horn Gap
To Multiplex Connection Between Tanks
Compound Filled Entrance Leads
Cast Iron Cover
Tube Hangers
Oil
Steel Rope for Lifting Cone Stacks
Connector
Steel Tank
Cones in Cross Section
Electrolyte
Oil
Cone Support
Insulating Tubes
Aluminum Cones, Complete
Connector
Metal Cone Base
Wooden Tube Support
Porcelain Insulator
Angle Iron Insulator Base

Fig. 26

treated fiber washers. The cell electrolyte partially fills the space between each cone, which is about 3 inch., and is in contact with part of the upper and lower cone. It is important that each cell contain the same amount of electrolyte, generally about one quarter pint in each cell, so as to have equal distribution of voltage over the arrester. The stack of cones is placed in a steel tank which is filled with oil for cooling and insulation The oil insulates the trays, conducts away the heat and prevents evaporation of the electrolyte. It also prevents the electrolyte from splashing out of the tray during discharges. A circular insulating barrier concentric with the cone stack is hung within the tank to increase the insulation between the stack and wall of the tank and to increase the oil circulation.

CHARGING OF ARRESTERS.

In developing the aluminum arrester, the manufacturers' intentions were to provide an apparatus that would be capable of discharging surges and line disturbances that would last a considerable lenght of time. The problem dealt with was that which is met in the design of all electrical apparatus, that of prevention of overheating. The current passing thru the arrester heats it and thus its capacity to take care of discharges lasting any lenght of time depends upon the quantity of current allowed to flow, and the heat-absorbing and radiating qualities of the arrester in general. The arrester is designed so that the current it will discharge is ample to lower dangerously high potentials to a safe value. But the lenght of time an arrester can discharge is reduced if any unnecessary current passes thru it. This unnecessary current is the current rush which would flow at the beginning of a discharge if the films were not properly formed. By keeping the films formed at all times, this initial

rush of current is prevented and the ultimate temperature rise of the arrester is minimized.

The arrester must be charged daily. An electrolyte could be substituted which would require less frequent charging, but it would necessarily be of high resistance in order to prevent a disastrous rush of current at charging. However, the high resistance electrolyte is extremely objectionable on account of its cutting down the discharge rate of the arrester.

The charging operation is as follows: First, the gaps of the arresters are closed for five seconds and opened again to normal position, thus charging the cells of the three line stacks (fig.36). Second, with the gaps still in normal position, the position of the transfer device is reversed and the gaps are again closed for five seconds and returned to the normal position. The complete charging operation takes but little time and should be performed daily.

The object of the transfer device is to

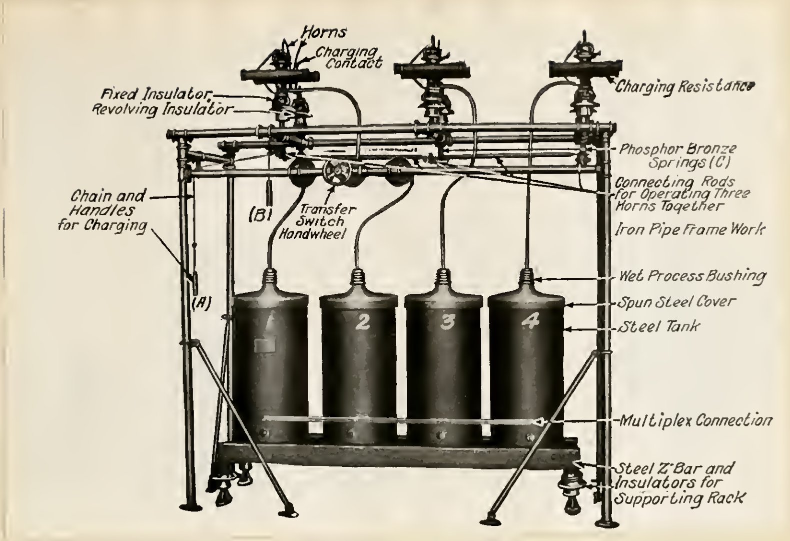

Horns
Charging Contact
Charging Resistance
Fixed Insulator
Revolving Insulator
Phosphor Bronze Springs (C)
Connecting Rods for Operating Three Horns Together
Chain and Handles for Charging
(B)
Transfer Switch Handwheel
Iron Pipe Frame Work
(A)
Wet Process Bushing
Spun Steel Cover
Steel Tank
2
3
4
Multiplex Connection
Steel Z Bar and Insulators for Supporting Rack

Fig. 36

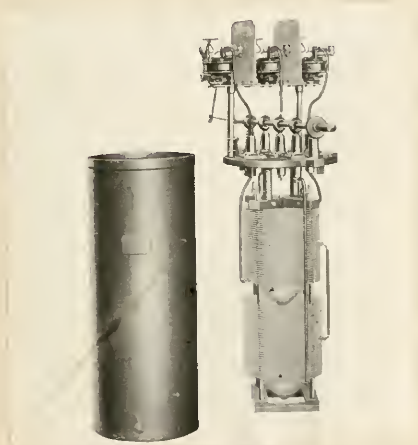


Fig. 46.

provide a means for interchanging the ground stack with one of the line stacks of cones during the charging operation so that the films of all the cells will be formed to the same value. For arresters up to 7250 volts the transfer device consists of a sliding type switch (fig. 46). For higher voltages the transfer device consists of a rotating switch which may be turned thru 180 degrees, and functioning as described above.

CHARGING RESISTANCE.

It is well known that any arc on a high-voltage circuit, especially if it alters the electrostatic condition of the circuit, is accompanied by oscillations. The resulting oscillations may be harmless or may result in local high-potentials as a result of resonance. This same phenomenon in a mild form has been noticed at times of charging aluminum arresters. The makers of this type of arrester appear to have recognized the danger of damage to apparatus from the operation of charging, and they now auxiliary apparatus. By the addition of charging resistances and charging contacts for the gaps all possibility of troubles due to charging is greatly minimized if not entirely eliminated. These resistances have been designed to dampen out any tendency to oscillate. Extensive observations and oscillagraph tests have clearly shown the effectiveness of the resistance.

The charging resistances are arranged to provide selective discharge paths to the cells.

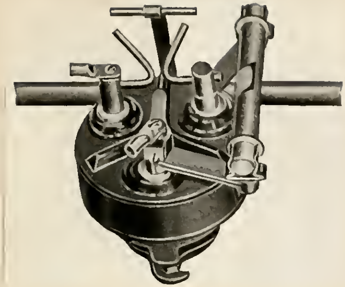


Fig. 56.

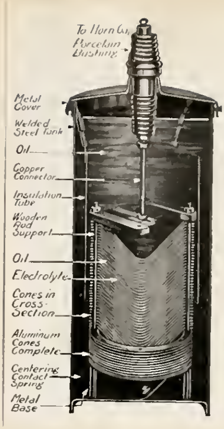

To Horn Ga
Porcelain Bushing
Metal Cover
Welded Steel Tank
Oil
Copper Connector
Insulation Tube
Wooden Rod Support
Oil
Electrolyte
Cones in Cross-Section
Aluminum Cones Complete
Centering Contact Spring
Metal Base

Fig. 76

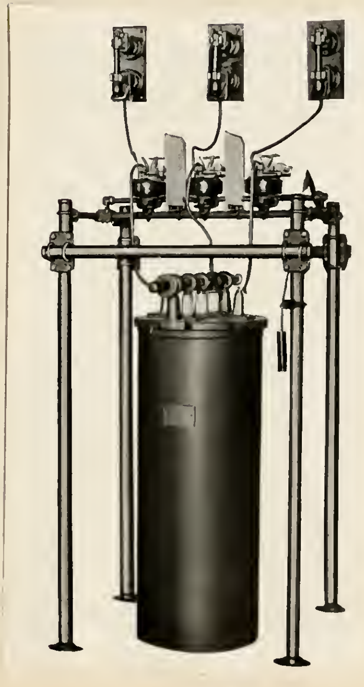


Fig. 66.

These paths consit of a main gap and an auxiliary gap, with a low resistance in parallel with the main gap. The auxiliary gap has a smaller setting than the main gap and is fitted with a charging contact, which at times of charging bridges the auxiliary gap and charges the cells thru the resistances. In the normal operation of the arrester this arrangement of gaps introduces selective paths for the discharge of lightning or other forms of potential surges.

One path consists of a small auxiliary gap, a low resistance and the aluminum cells. All discharges will first spark across the auxiliary gap and pass to ground thru the resistance and the cells. If, however, the quantity of the discharge is too great to be dissipated thru this path, the discharge automatically shunts to the main gap where it is not impelled by the resistances. The resistance is of low value, and consequently all but the heaviest discharges are taken care of by this auxiliary path.

One type of charging resistance and charging contact is shown in fig 5G, a gap for 1000-7250 volt arrester in fig6G.

In general, it may be said that charging resistances do not sacrifice any of the valuable features of an arrester, and by their addition the arrester is made more sensitive, reliable and durable.

CONSTRUCTION.

The construction of arresters for voltages from 1000 to 7520 is illustrated in figs. 4, 5, and 6G. The cells are placed in a single tank which is grounded, and the gaps, charging resistances, and charging contacts for each phase are mounted on a single insulator. The closing of the horn gap for charging is effected by a rotating shaft of insulating material carrying three metallic projectors which, when the shaft is rotated, bridge the three gaps and allow the necessary charging current to flow thru each cell. The arrester may be disconnected by means of separate detachable fuses. The transfer switch shown is of the sliding type. For arresters of voltages from 7250 to 75000 the construction is as shown in fig 7G. The cone stacks are placed in separate tanks (fig 3). The tanks are insulated from the ground. For the lower limits of voltage in this type of arrester the gap and auxiliaries may be of the type shown in fig 5G. For voltages above 75,000 the elliptical type tank is used. This type

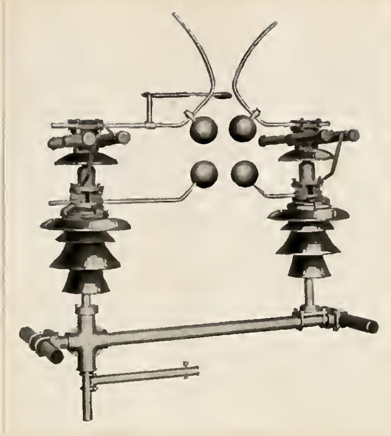


Fig. 8G.

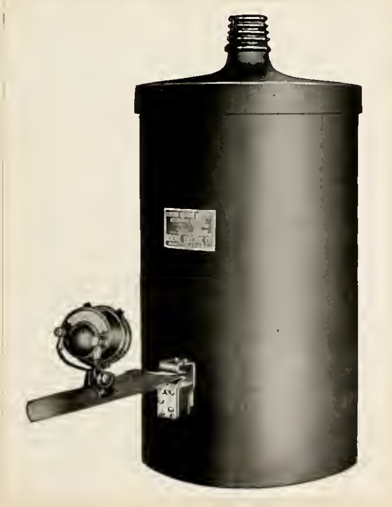


Fig. 9G.

is illustrated in fig. 26. Owing to the large number of cones necessary for this range of voltages the cone stacks would become unwieldy if the lower-voltage type of construction were used. Therefore, in the elliptical tank arrester the cones for each phase are put into two separate stacks which are insulated from the base of the tank and the tank is grounded.

The advantage of the grounded tank design as compared with the insulated tank, for the very high voltages, are: greater safety in operation, economy of flow space, and increased stability since they have larger bases and rest directly on the concrete foundations.

All tanks are fitted with drain valves, to which pipes can be connected for transferring the oil to another tank or drain in case of fire.

SPHERE GAPS.

The use of sphere gaps with aluminum cell arrester is the most recent and one of the most important advances in the art of electrolytic arrester design. The latest development in this direction consists of a somewhat complex arrangement combining sphere gaps, horn gaps and resistances (fig. 8): the object being to obtain a quick and free discharge of disturbances of steep wave front across sphere gaps without resistances in series. If the arc persists across this gap it rises to another sphere gap which has resistance in series to dampen the oscillations of energy. Other lightning discharges are dealt with by a horn gap of the ordinary type mounted immediately above the second sphere gap.

The advantage of the sphere gap over the horn gap is that it is "faster" for sudden impulses in other words it has a shorter di-electric spark lag. All aluminum arresters are now equipped with shpere gaps except those for voltages up to and including 7250 volts. The diameter of the copper rod used for the horn gaps of the latter is so large in proportion to the gap; that the effect is the same as if spheres were used. It may, therefore, be considered that all arresters are provided with sphere gaps.

CHARGING CURRENT INDICATOR.

When aluminum arresters were first devised the users were unable to learn the condition of the cells except by observing the size of the charging arc, which is very indefinite and unsatisfactory method, or by removing the cells and making an examination of each cell which is a long and expensive process. Now, the charging current is a good indication of the condition of the arrester cells. An arrester in good condition has a charging current of approximately 0.25 ampere on 25 cycle circuits, 0.30 ampere on 40 cycle and 0.40 ampere on 60 cycle circuits, and the amount of current can readily be determined by a devise brought out by the manufacturers of aluminum cells.

The essential parts of the charging current indicator are an ammeter mounted on a specially constructed switch stick and a set of jacks (fig. 9G). These jacks are so connected in the arrester circuit that when

the ammeter switch stick is inserted in them and the horn gaps short-circuited, the charging current flows thru the meter. On the single tank arresters the ammeter jacks are connected to the horn gaps. On the round tank arresters (fig. 96) the jacks are connected to the tanks. The tank supports are provided with insulating strips. On the elliptical grounded tank arresters the jacks are connected on top of the neutral bushing.

THE OXIDE FILM ARRESTER.

Introduction.

Lately a new type of lightning arrester has been devised, the Oxide Film Lightning Arrester. It has all the advantages of the aluminum cell arrester, but does not require special attention such as charging which is inherent with the aluminum cell. It contains no liquid electrolyte or inflammable material, and can be located outdoors as well as indoors, as in the case of the aluminum cell. For the past fifteen years the results obtained with the aluminum cell have proven so conclusively that it is the only type capable of affording protection in modern high-powered circuits, as to lead to its almost universal adoption. However, since the oxide film combines all the good qualities of the aluminum cell, and has even more desirable features, as mentioned above, it is logical that the choice between the two types will lie with the oxide film type.

Principle.

The oxide film arrester like the aluminum arrester, acts as a counter-emf. equal to the normal circuit voltage, but holds back the normal machine voltage. Thus the discharge is limited to the energy of overvoltage, as in the aluminum arrester, and like the latter, the oxide film arrester can continuously discharge recurrent surges, such as arcing grounds etc., without endangering itself, sufficiently long to notice and eliminate the disturbance.

The functioning of this arrester depends on the fact that certain dry chemical compounds can be charged with extreme rapidity from very good conductors of electricity to almost perfect non-conductors by the application of a slight degree of heat. Lead peroxide is a good example of such a substance. It has a specific resistance of the order of one ohm per cubic inch. The resistance varies with the pressure to which it has been compressed. At a temperature of about 150 deg.cent.

the lead peroxide (PbO_2) will be reduced to red lead, commercially known as minimum (Pb_3O_4). This has a specific resistance of about 24 million ohms per cubic inch. At slightly higher temperatures this minimum will be reduced through the sesquioxide (Pb_2O_3) to lightarge (PbO) which is practically an insulator.

Lead peroxide is normally in the physical state of a powder. If this powder be placed between two electrodes and a current passed, the temperature due to the resistance at the contact of the peroxide the metal will cause heat to be generated locally at the surface. When this heat is sufficient to create a temperature of about 150 deg. cent. a film of the lower oxides of lead forms, producing a film of insulation which stops the current. This method of film formation is rather irregular and slow. There are several different methods which may be used in the formation of the insulating film. In commercial manufacture the preferable method is to put the

film on before assembly, by dipping the plates in a suitable insulating varnish which gives them a coating just thick enough to hold back the circuit voltage. Then after assembly voltage is put on the cell for testing it and sealing any holes or defects which may exist in the varnish film.

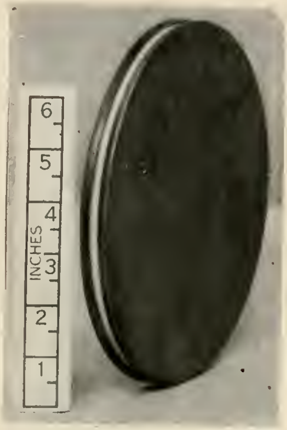


Fig. 1 H.

The cell of the oxide film arrester, shown in figure 1H, consists of two circular metal plates as electrodes which are kept about .5 in. apart by a porcelain ring as shown in the figure. The space between the electrodes inside

the porcelain ring is filled with the active material, lead peroxide, which is put in under moderate pressure. The insulating film holds back the voltage about 250--300 volts per cell. Then only a small leakage of a few milliamperes passes at normal voltage. As soon as the voltage rises slightly above normal the film punctures in one or more microscopic points, the lightning charge meets with practically no resistance (The ohmic resistance being less than one ohm per cell.) and flows to earth (Fig. 2H). The dynamic current starts to follow but because of the fact that the insulation was punctured in such fine points, the current density near these points is exceedingly great. This results in a localized heating which speedily raises thetemperature to a value sufficient to change to insulating litharge all the conducting peroxide in this minute path of the current flow in contact with the electrodes. The film consequently reseals, stopping the flow of dynamic current. The action is so rapid that its duration

cannot be measured on an oscillograph giving two-thousand cycles per second, that is to say, the action of resealing occurs in less than one four thousandth part of a second after the excess of lightning voltage has ceased.

A certain range of voltage is necessary to pierce any given insulation. The exact voltage depends not only upon the dielectric strenght and thickness of the insulation but also upon the relation of the dielectric spark lag to the duration of the super-spark potential and the frequency of alternations of the transient surge.

Since an arrester is to give full protection to the insulation in shunt with it, it must quickly relieve any abnormal voltages before damage is done to the insulation. Frequently tests are made with the arrester and insulation in parallel. A standard method has been devised and is known as the equivalent sphere gap test. Both the insulation and arrester are compared by comparing each to the equivalent sphere gap.

The equivalent sphere gap of the oxide film arrester may be analyzed into separate and distinct parts. First, there is the equivalent sphere gap of the main gap in series with the cells. Second, the equivalent sphere gap to initiate a discharge thru the insulating film on the plate surface of the cell. Third, there is the equivalent sphere gap of the resistance drop of the current discharging thru the powdered peroxide in its path. Fourth, there is the equivalent sphere gap of the inductance of the arrester.

Commenting on these factors in their relation to this arrester, the main gap is itself a sphere gap, which has the fastest spark of any practical gap. The gap setting is only slightly above the normal voltage of the circuit.

The equivalent sphere gap, of the film is several times greater than the thickness of the film because solid material has a greater dielectric spark lag than air, but with this multiple of the thickness of the film the equivalent sphere gap is

still low. Since peroxide is a good conductor, the series resistance in the path of the discharge is insufficient to give an undesirable voltage drop. As to the inductance of the arrester, it has a minimum value due to the fact that each cell is only 0.5 inch long, and these cells are placed one on top of the other. In other words, the total lenght of the arrester, which is a measure of the inductance, is short as compared to the necessary lenght of conductor from line to earth.

Performance Tests.

In designing arresters of any type, actual line conditions which must be taken care of, cannot be reproduced. Hence the final test of the arrester lies in its commercial operation on industrial systems. This type of arrester was installed on a number of lines and after several years of operation numerous installations were made, for voltages from 110 to 33000, and have proven their protective value. Two performance tests will be described here, by means of oscillogram curves.

Figs 3&4, show the action on a recurrent oscillation. Thetest was made in the following manner: A surge was produced by a large condenser connected to an alternating-current supply and discharging across a spark gap through an inductance. The value of the inductance was chosen so as to produce a frequency of 1200 cycles, which would fall within range of the oscillograph. This surge or continual oscillation was impressed upon the piece of apparatus to be protected, in this case, a trans-

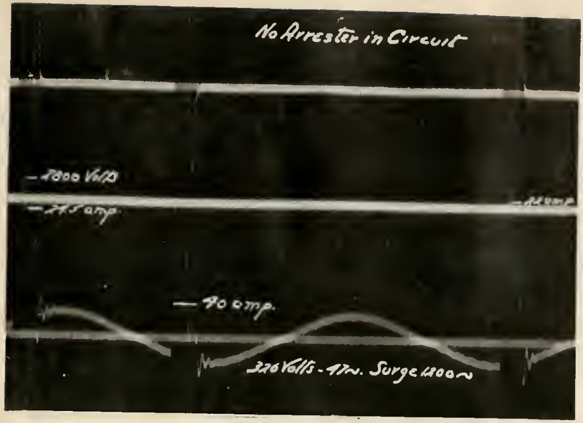

No Arrester in Circuit
—4800 Volts
—24.5 amp.
—22 amp.
—40 amp.
320 Volts - 47~. Surge 1200~

Fig. 3 H

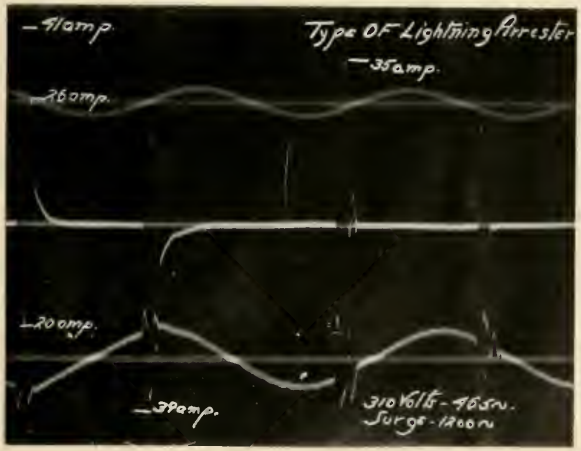

—41 amp.
Type OF Lightning Arrester
—35 amp.
—26 amp.
—20 amp.
—39 amp.
310 Volts - 46.5~.
Surge - 1200~

Fig. 4 H

former energized by another supply circuit. Fig. 3H. shows the oscillogram without protection to the transformer. Fig. 4H shows the oscillogram with the arrester shunting the transformer.

In fig 4H, the lowest curve shows the oscillations superimposed on the 320 volt, 47 cycle power supply of the transformer, rising to surge peaks of 2800 volts. The upper curve shows the oscillating currents passing thru the transformer rising to peaks of 40 amperes. The lower curve in fig 4H shows again the circuit voltage wave impressed upon the transformer, with the oscillation peaks sharply cut off at a maximum voltage of 60 per cent above circuit voltage, the value for which the spark gap was set. This curve, showing the oscillations very greatly cut down from the high values in the unprotected circuit to the unsymmetrical values in the protected circuit, well illustrates the characteristic action of this type of "counter-emf." arrester to which the oxide film and aluminum cell arresters belong. The half waves

of oscillation in the same direction as the circuit voltage are greatly reduced, by the limitation of the voltage to 60 per cent above normal, while the reverse half waves, which lower the instantaneous circuit voltage, are less affected. Corresponding thereto, the discharge current thru the arrester, the middle oscillogram in fig 4H. is unsymmetrical also; the middle curve shows the current oscillations passing thru the arrester, with peaks of 35 to 41 amperes; in the first and second oscillation of fig 4H the first and third half wave of oscillating voltage is cut off, and the first and third half wave of the oscillating discharge current therefore higher than the second half wave of oscillating voltage in opposition to the circuit voltage, therefore not raising the circuit voltage. The third oscillation of fig 4H happens to start with a half wave of oscillating voltage in opposition to the circuit voltage, and the first half wave oscillating discharge current thru the arrester, in the middle curve, thus is

smaller than the second half wave; the second half wave of the oscillation is cut down in the voltage and therefore gives the maximum discharge current, 35 amperes in this case.

The protective action of the oxide film arrester against a single non-oscillating impulse produced by opening a highly inductive 550 volt direct current circuit, a railway motor in this case, is shown by the oscillograms in figures 5&6. The lower curve of fig. 5H shows the oscillogram of the impulse in the 550 volt circuit rising to 7000 volts. The upper curve merely is a 60 cycle timing wave, to enable measuring the duration of the impulse. Fig. 6H shows the same circuit, with an arrester shunting it. The impulse voltage rises to the value for which the discharge gap of the arrester is set, in this case 2200 volts. Then the arrester discharges, and the voltage instantly drops back to normal, while a slowly decreasing discharge current thru the arrester dissipates the magnetic energy of the impulse.

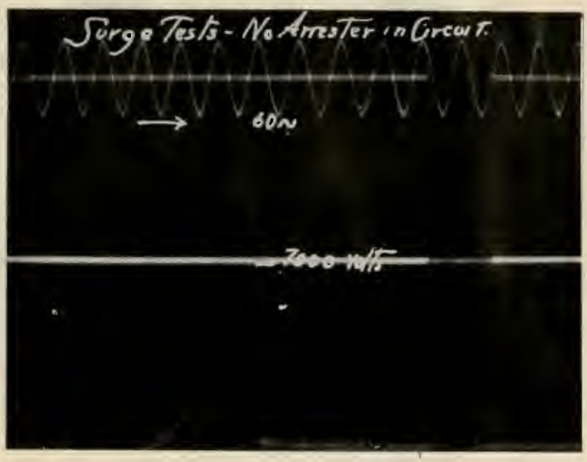

Surge Tests - No Arrester in Circuit.
60~
2000 volts

Fig. 5H

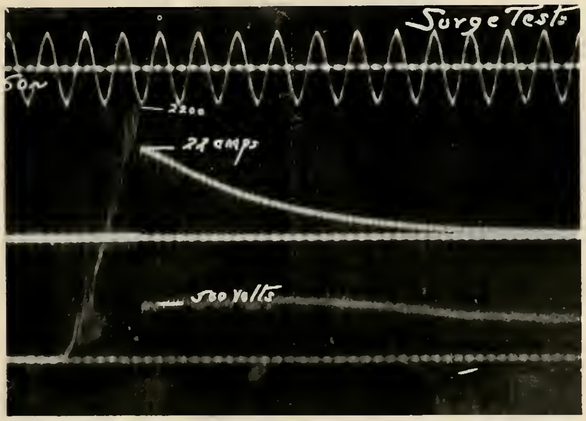

Surge Tests
60~
2200
22 amps
580 volts

Fig. 6H

[illegible]

[illegible]

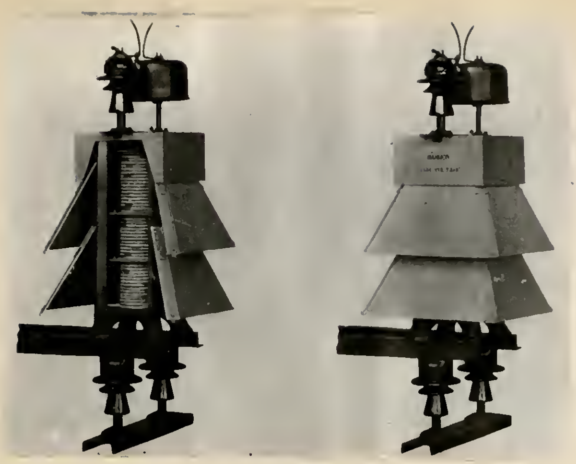


Fig. 8H

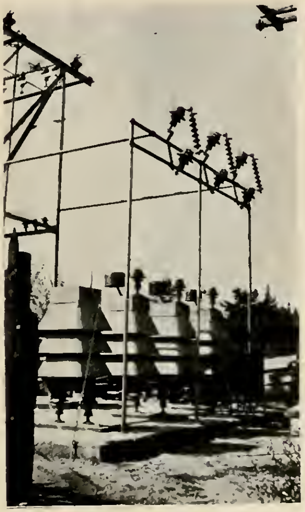


Fig. 9H

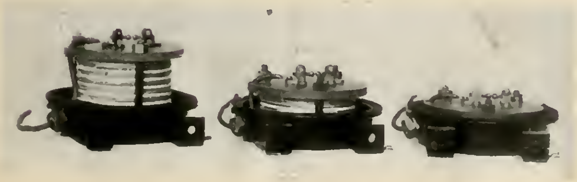


Fig. 7H

A number of cells, depending on the voltage of the circuit, of the type shown in fig. 1H are piled on top of each other. with a spark gap in series, and for moderate voltages, are encased as shown in fig. 7H. The cells are hermetically sealed, and can be installed outdoors as well as indoors, requiring for outdoor installations merely some protection by petticoats as shown in fig 8H, to protect the cells from short-circuiting. Fig. 9H shows an outdoor installation of a 33000 volt arrester with three-phase stacks and the ground stack of cells, protected by metal petticoats. It shows also the spark gaps on the line side of the arresters, with protected sphere gaps to give instantaneous action and horn gaps for extinction.

The need of using this spark gap in series is still the only undesirable feature which this arrester shares with the aluminum cell arrester.